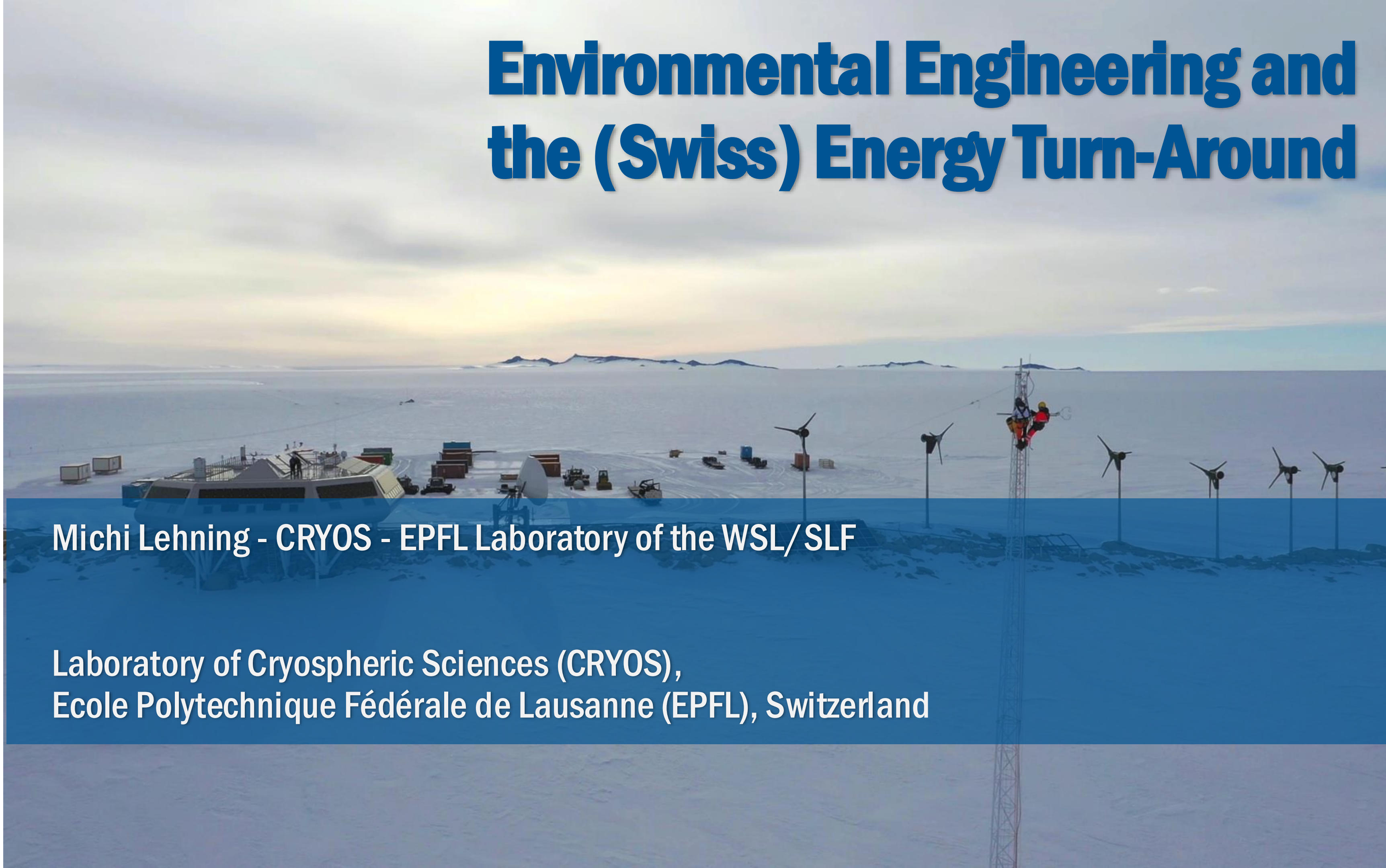

Environmental Engineering and the (Swiss) Energy Turn-Around

Introduction to Environmental Engineering 2024

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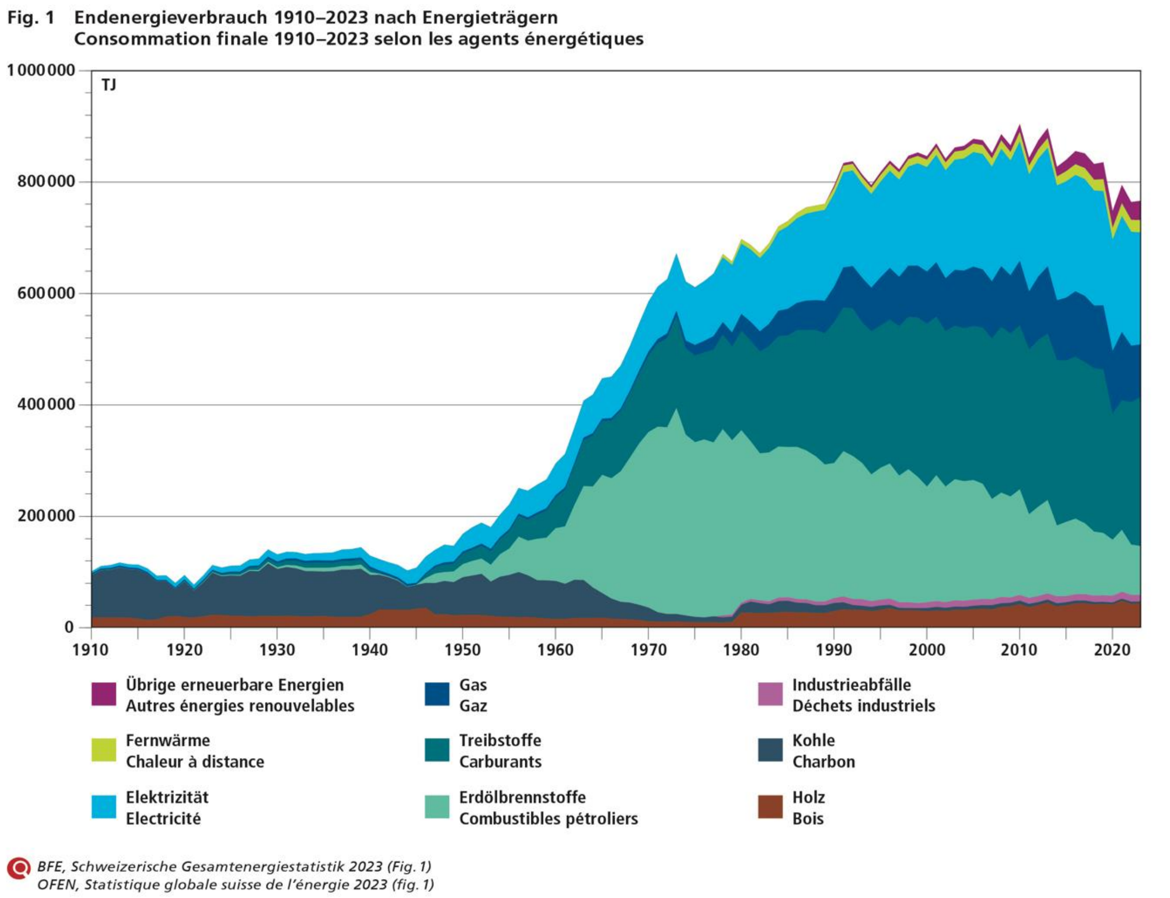
Laboratory of Cryospheric Sciences

Content / Outline

- The Swiss energy situation and how it will change in future
- What we (don't) know about the wind in the mountains
- Why Alpine PV would work well for Switzerland
- The radiation energy balance in complex snowy terrain
- Wind, Snow and Infrastructure: Problems and Solutions
- An Urban Energy Story
- Swiss Scenarios, Weather Value and Policies

➡ Let's see what environmental engineering can contribute for a Future Renewable Switzerland

Total Energy Consumption in Switzerland



Good News:

Total consumption is decreasing

Bad News:

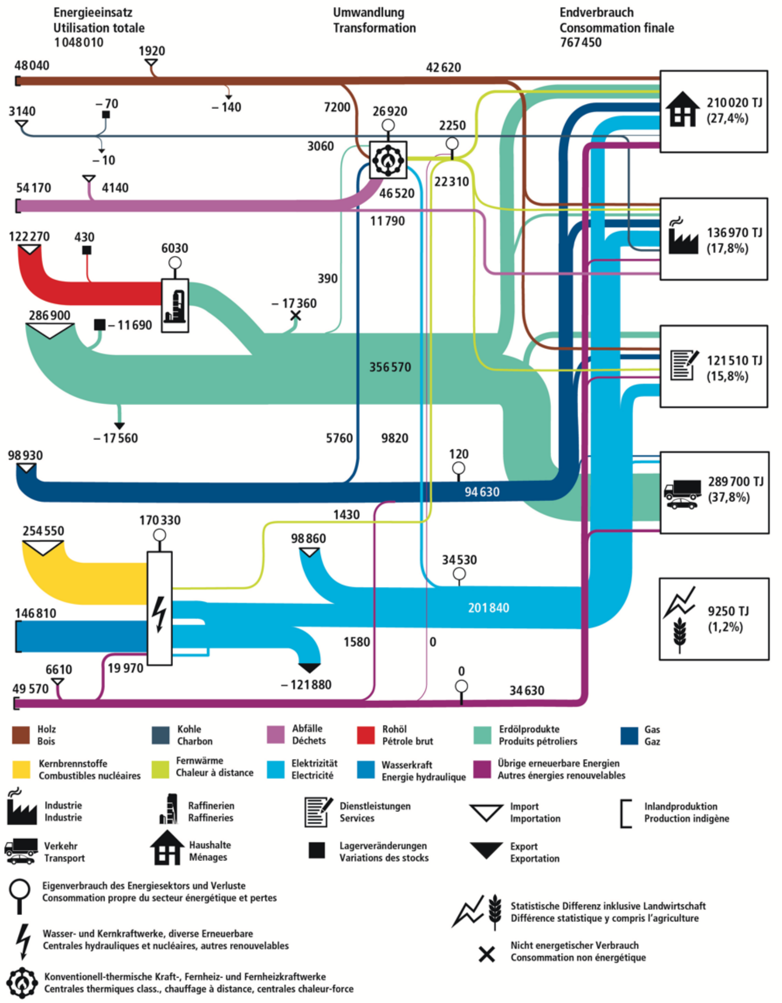
Most consumption is not renewable

Energy from Source to Consumer

- Only little electricity goes into transport sector (thus far)
- Transport leads consumption of carbon-based energy
- Industry and Households are heavy consumers of energy

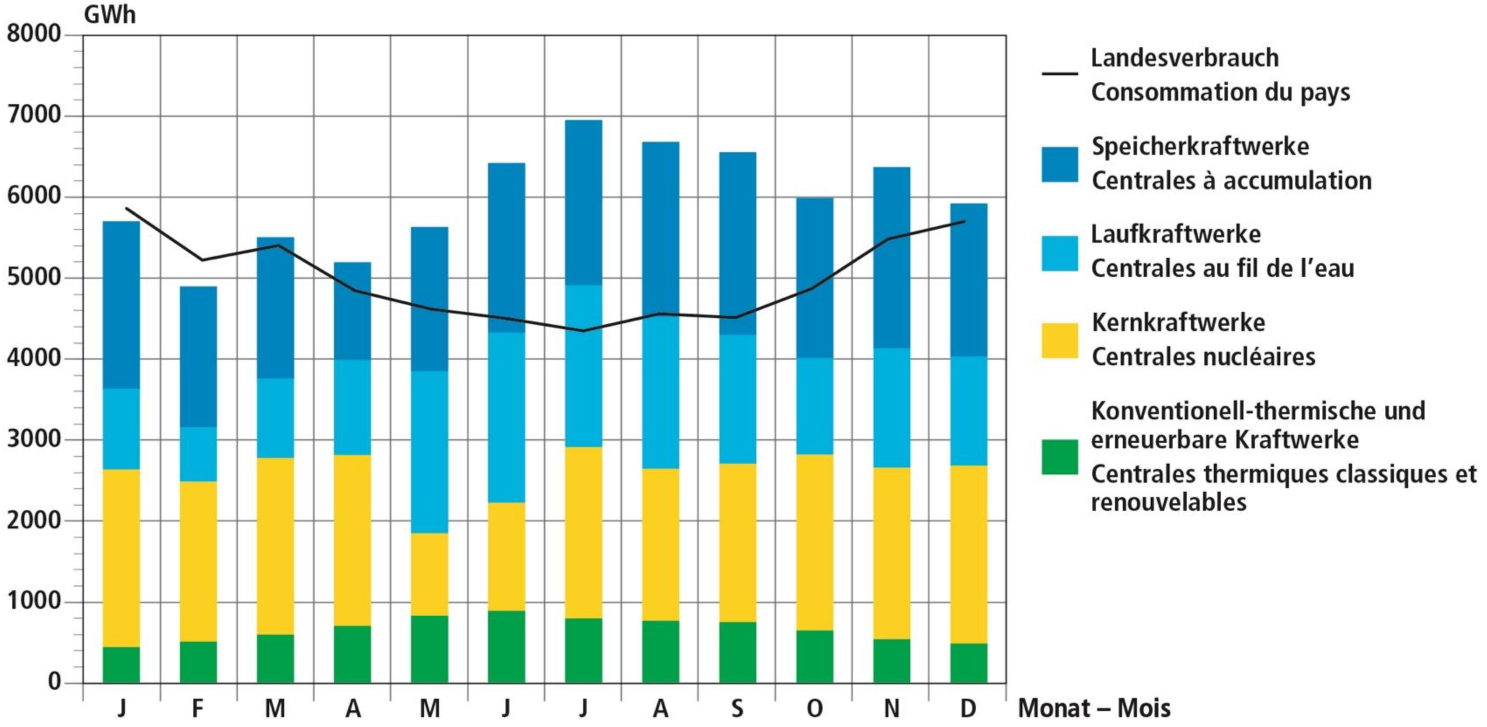
Fig. 5 Detailliertes Energieflussdiagramm der Schweiz 2023 (in TJ)
Flux énergétique détaillé de la Suisse en 2023 (en TJ)

BFE, Schweizerische Gesamtenergiestatistik 2023 (Fig. 5)
OFEN, Statistique globale suisse de l'énergie 2023 (fig. 5)



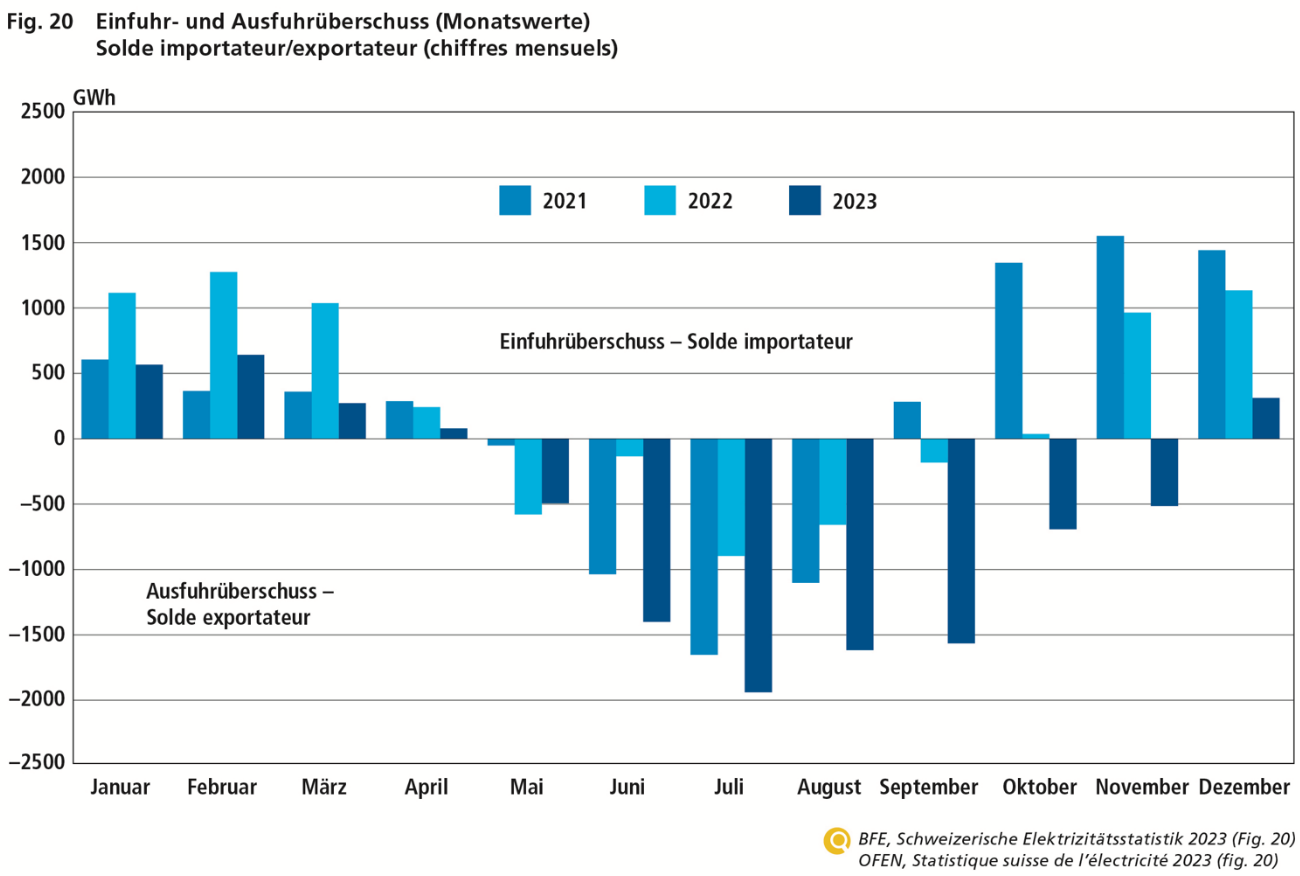
Now let's look at electricity

Fig. 10 Monatliche Erzeugungsanteile und Landesverbrauch im Kalenderjahr 2023
Quotes-parts mensuelles et consommation du pays durant l'année civile 2023



BFE, Schweizerische Elektrizitätsstatistik 2023 (Fig. 10)
OFEN, Statistique suisse de l'électricité 2023 (fig. 10)

Switzerland exports electricity during the summer ...

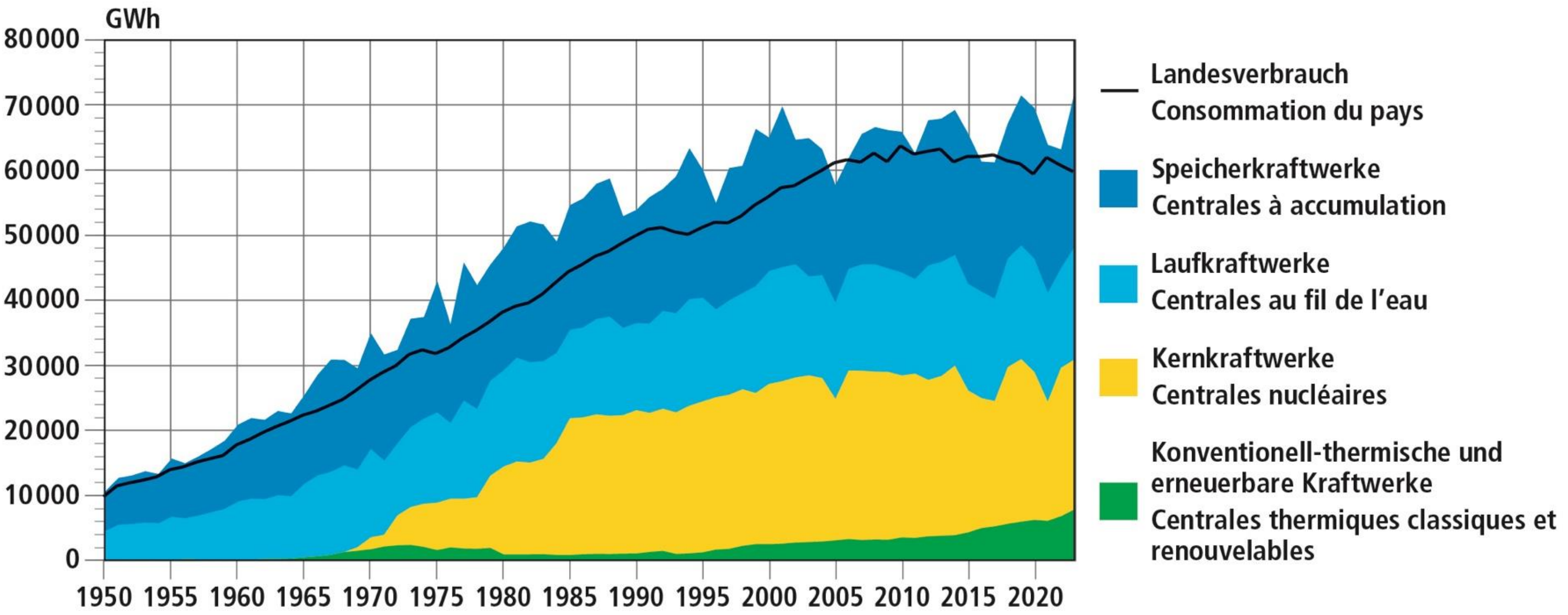


… but needs to import during winter;

winter deficit will grow in the future;

Hydropower is the backbone, nuclear should be replaced ….

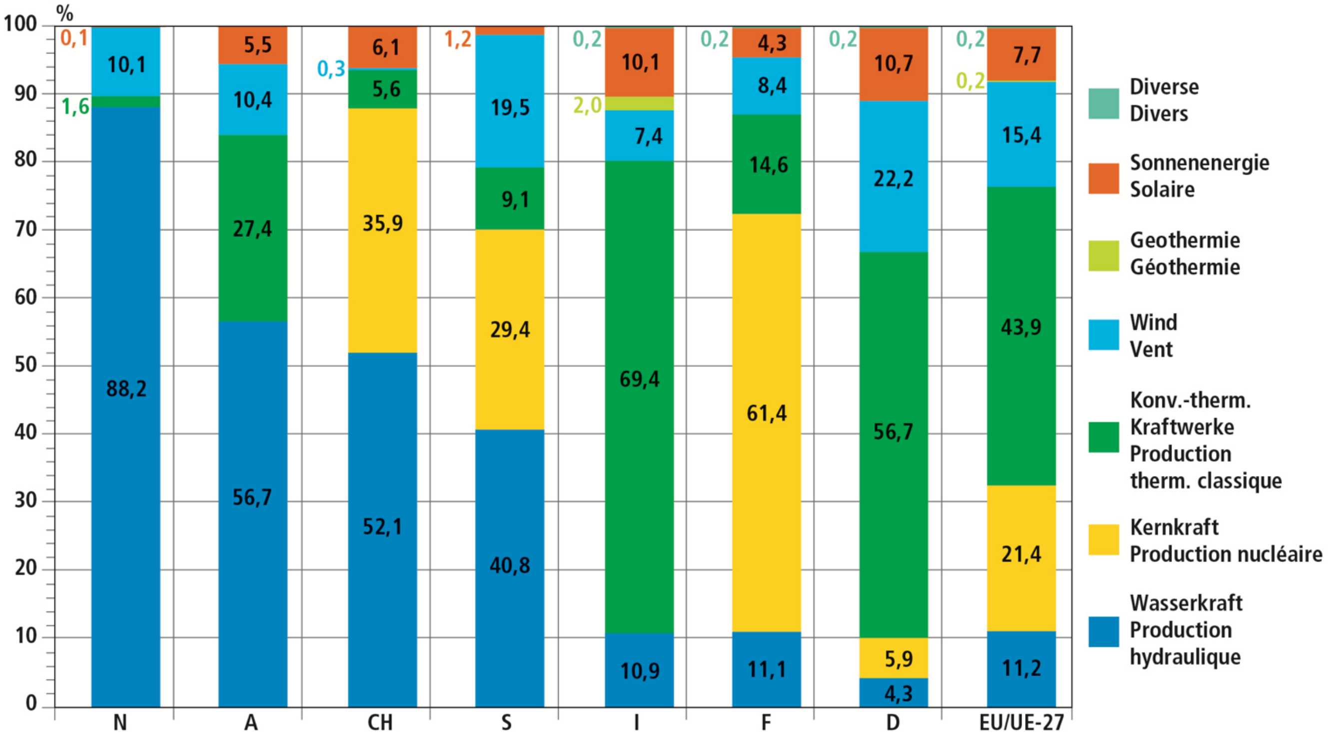
Fig. 9 Entwicklung der einzelnen Erzeugerkategorien seit 1950
Evolution des différentes catégories de production depuis 1950



BFE, Schweizerische Elektrizitätsstatistik 2023 (Fig. 9)
OFEN, Statistique suisse de l'électricité 2023 (fig. 9)

A comparison of electricity supply with other countries

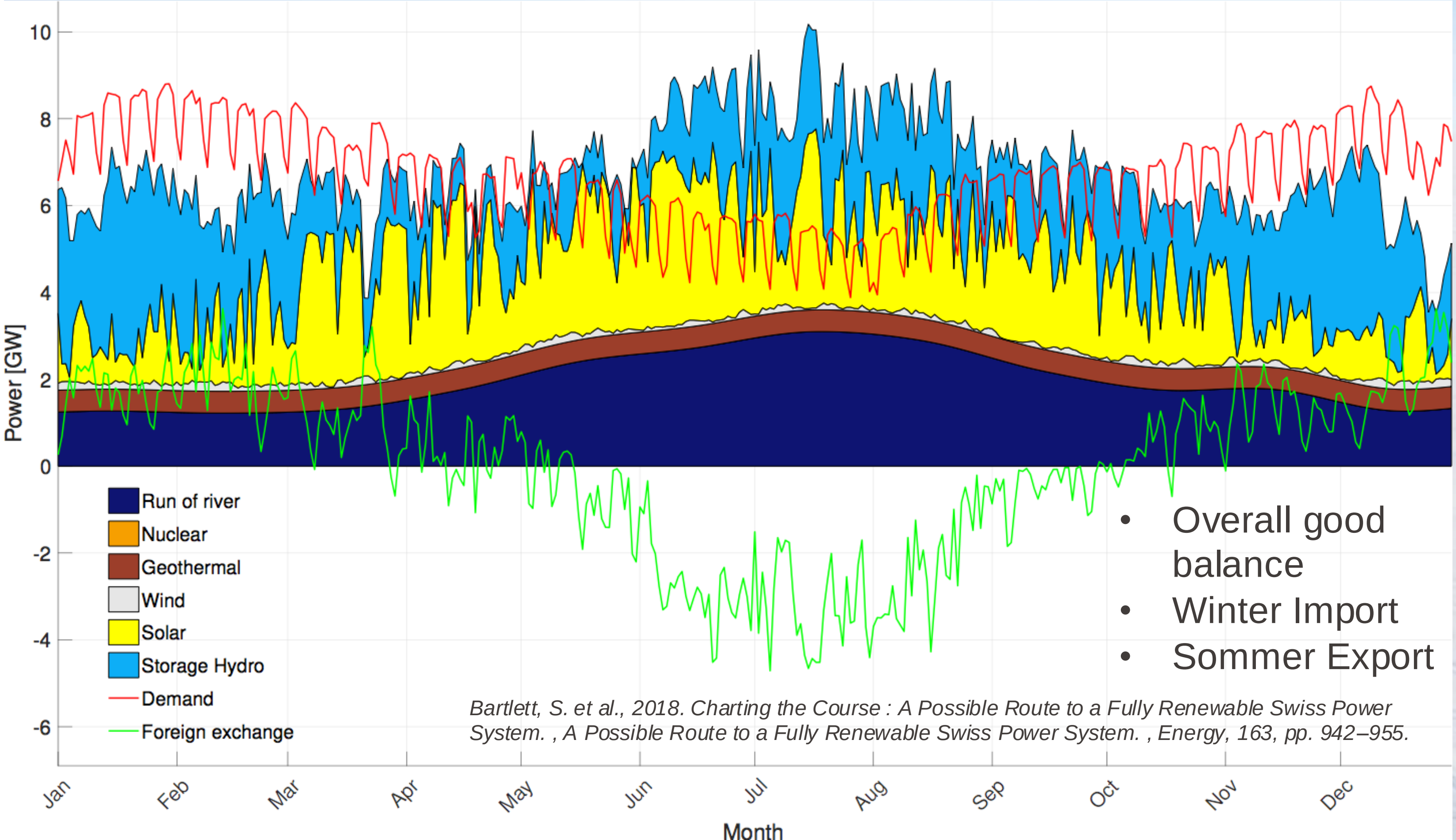
Fig. 5 Produktionsstruktur einiger Länder 2022
Structure de production de divers pays 2022



BFE, Schweizerische Elektrizitätsstatistik 2023 (Fig. 5)
OFEN, Statistique suisse de l'électricité 2023 (fig. 5)

EPFL

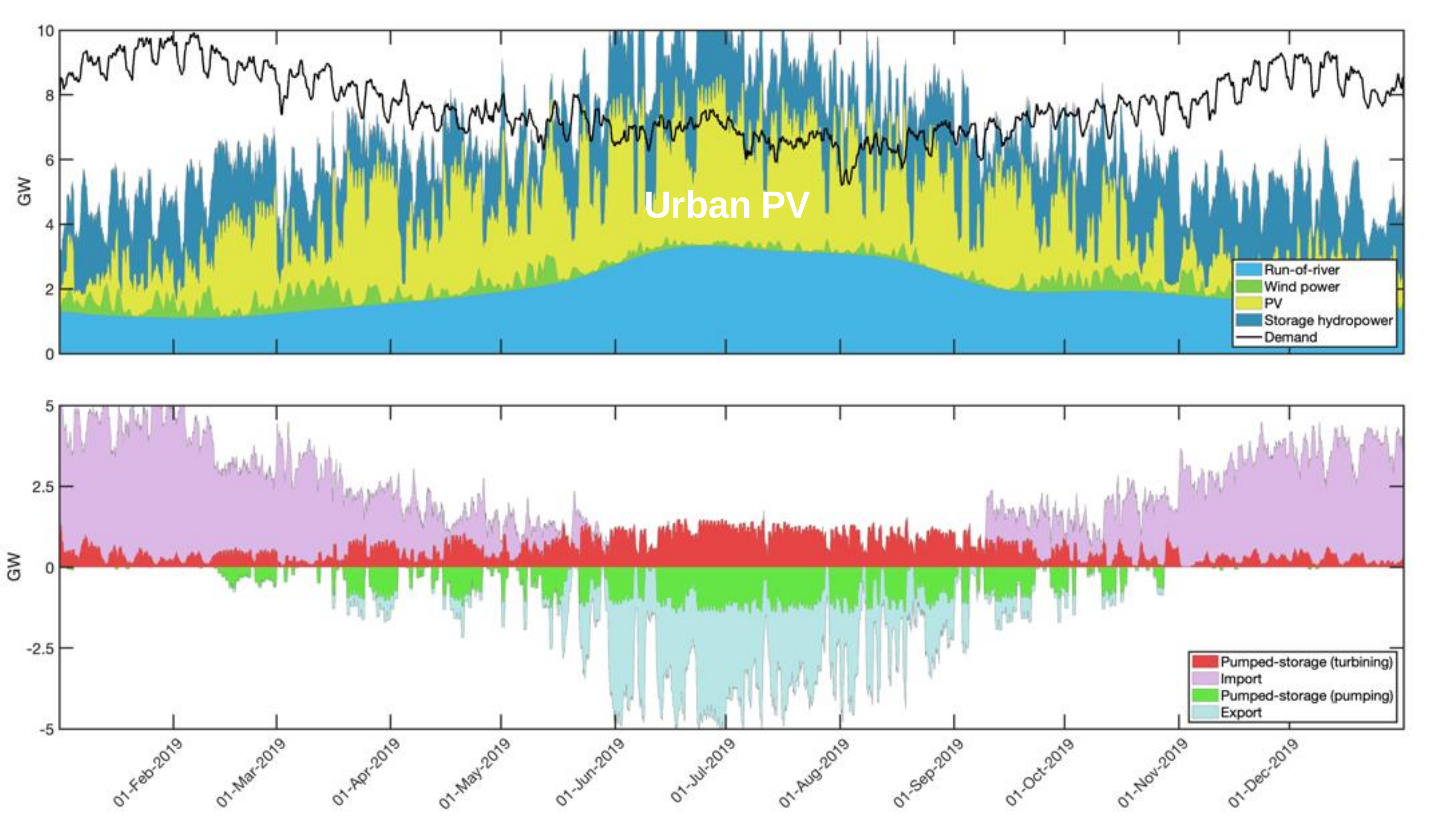
Hydropower is the backbone, nuclear should be replaced ....



- Overall good balance
- Winter Import
- Sommer Export

Bartlett, S. et al., 2018. Charting the Course : A Possible Route to a Fully Renewable Swiss Power System. , A Possible Route to a Fully Renewable Swiss Power System. , Energy, 163, pp. 942–955.

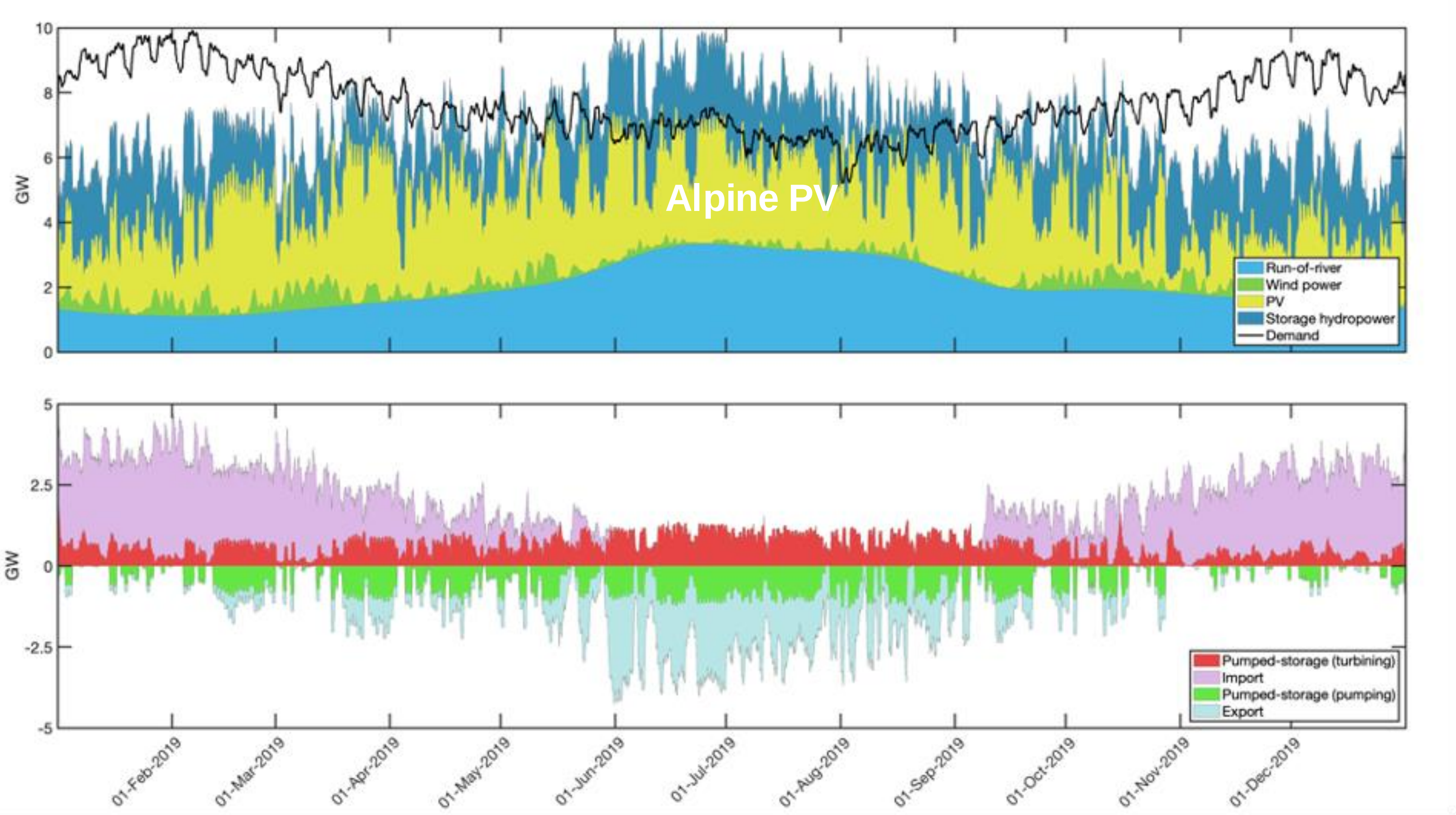
If we build "conventional", urban PV



(PV + Wind: 15 GW) **Winter Import**: 14.5 TWh

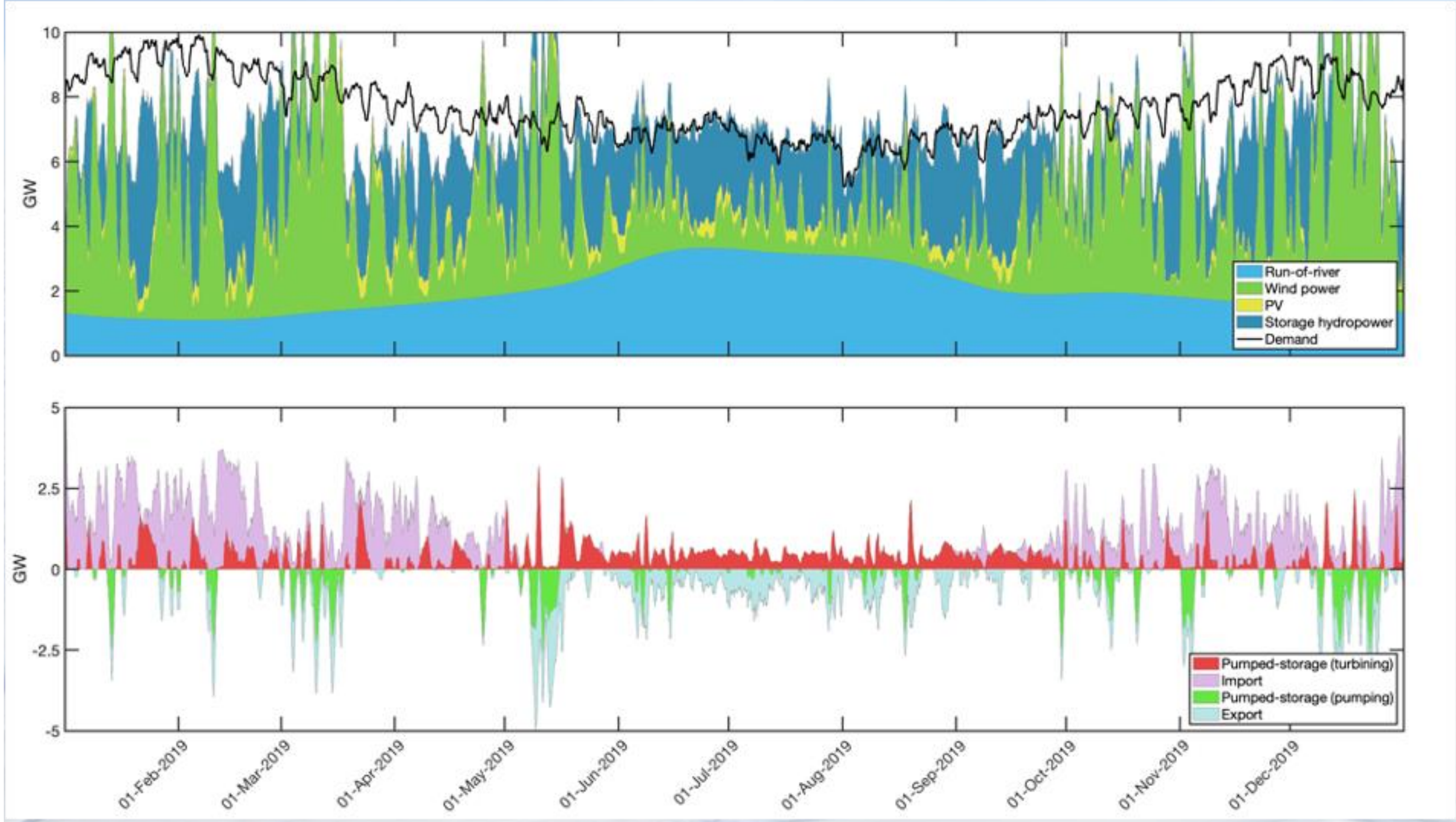
EPFL

If we build more Alpine PV



(PV + Wind: 15 GW) **Winter Import**: 14.5 TWh → 11.7 TWh

If we build more Wind Installations



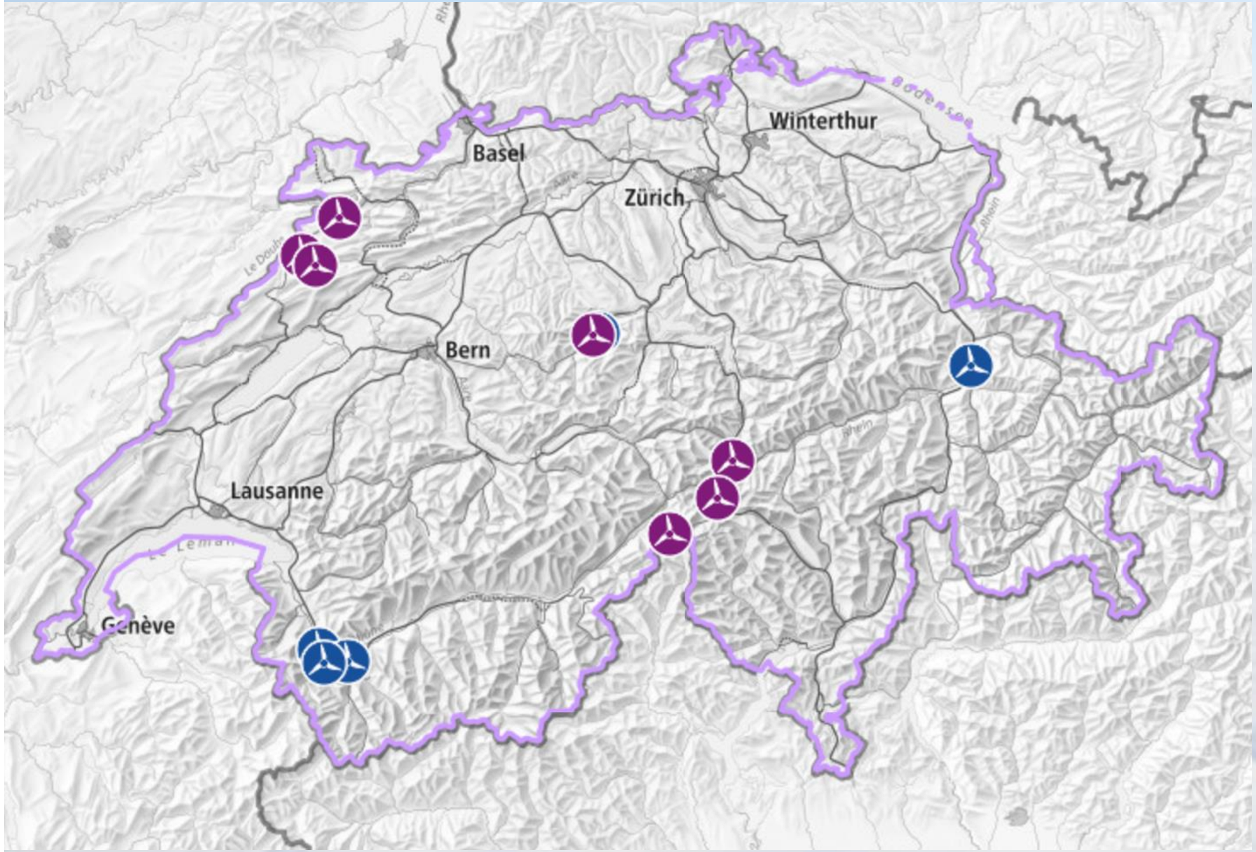
(PV + Wind: 15 GW) **Winter Import**: 14.5 TWh → 11.7 TWh → 6.5 TWh (88% Wind)

EPFL

First Summary

- Switzerland still is heavily dependent of fossil energy including for fuels and industry
- Switzerland has a strong hydropower backbone, which produces about 60% of the electricity demand
- Switzerland needs to import electricity in winter (about 4 TWh in 2022/23), this will increase in future
- The future winter import can be reduced by building Alpine PV and wind installations

Wind Energy in Switzerland – a sad story up to now



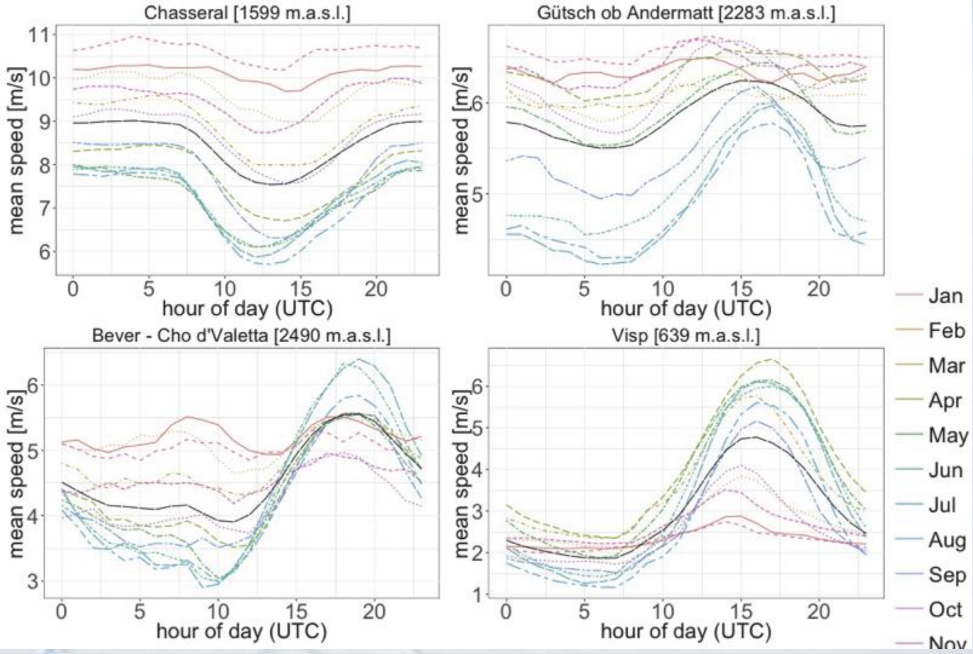
Very few current installations;

Very long realization times: ~10 years;

Attempts on the way to speed up the process;

Wind Features in Switzerland

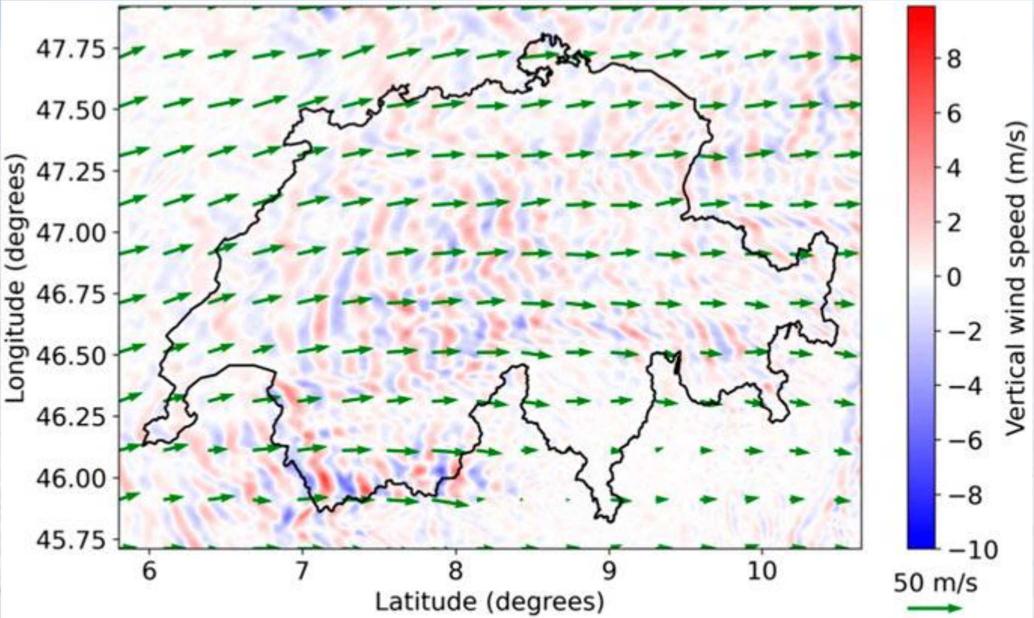
Laseier Wind Schwendetal (AI)

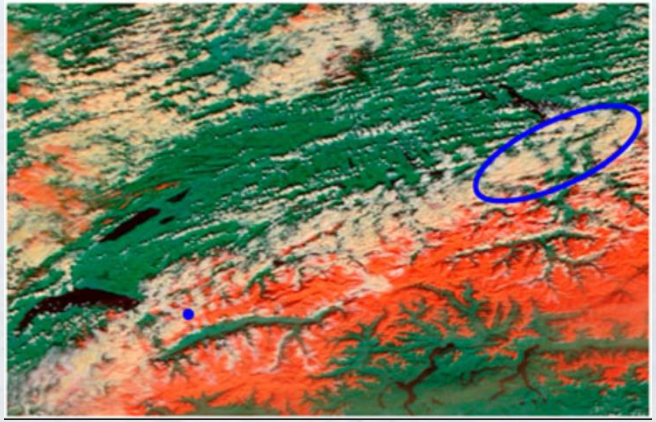


The terrain has multiple effects on wind speed and direction; can lead to strong acceleration of the flow as for example for the Laseier wind. Typical wind patterns for typical Swiss locations are shown above; many locations show favourable conditions for wind energy harvesting particularly also for the winter time.

Kruyt, B., M. Lehning, and A. Kahl. Applied Energy 192 (April 15, 2017): 1–11.

Wind Features in Switzerland caused by the complex terrain

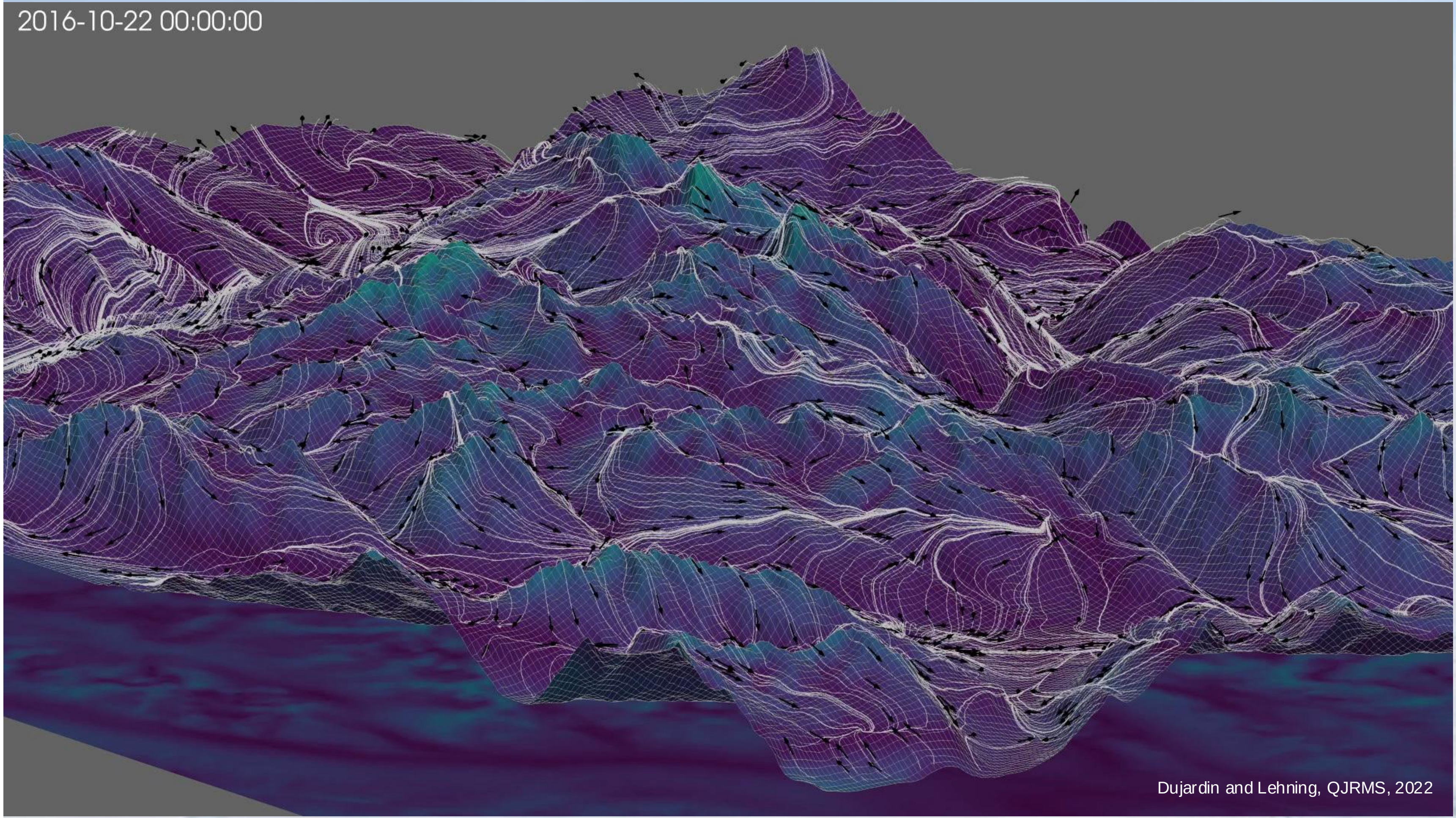




Föhn and mountain waves are two important flow features that lead to spatial variation of wind speeds and locally increased velocities in complex terrain. A wave pattern (red and blue colours showing up- and downward vertical velocities) for a generally westerly flow field (green arrows) is shown on the left panel. The right image is showing wave cloud patterns from a satellite image.

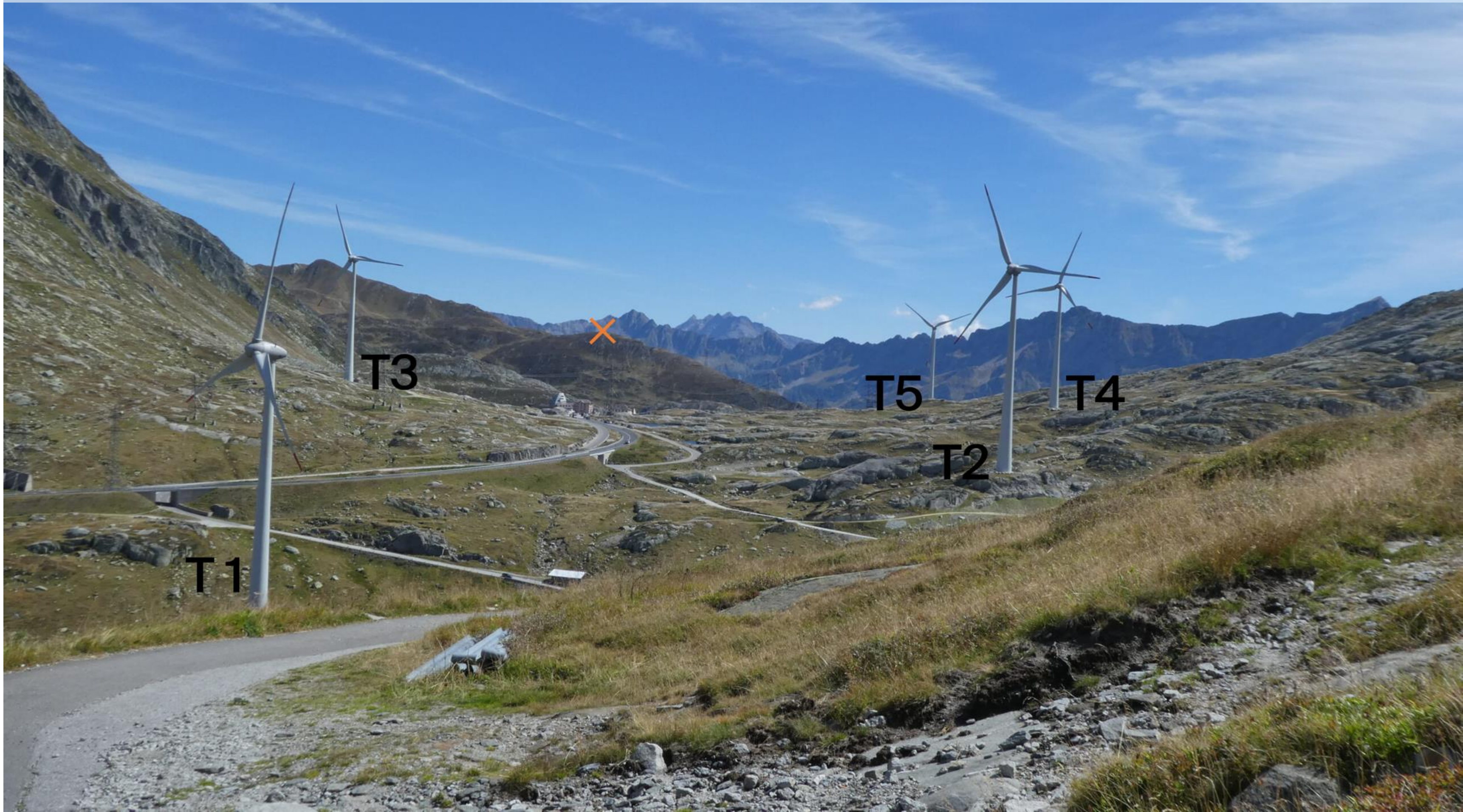
Kristianti, Fanny, et al. Frontiers in Energy Research 12 (2024): 1379863.

High Resolution Wind Simulation with Machine Learning

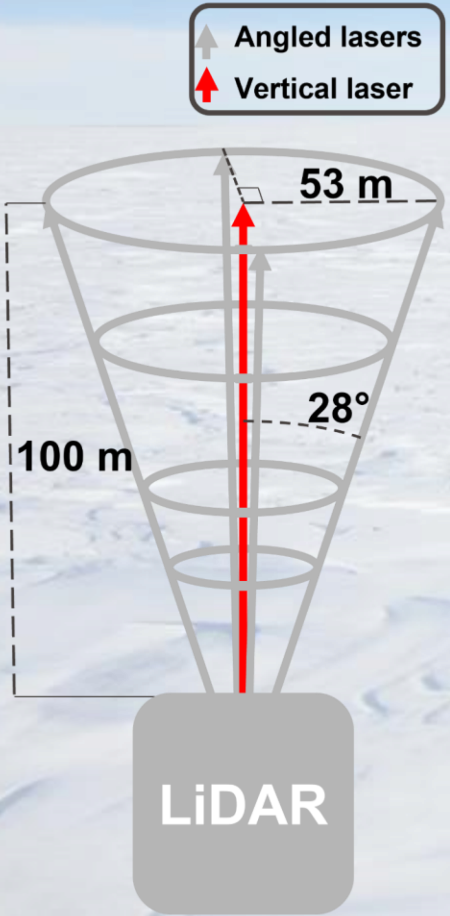


Dujardin and Lehning, QJRMS, 2022

Let's go to the field: Windpower production at Gotthard



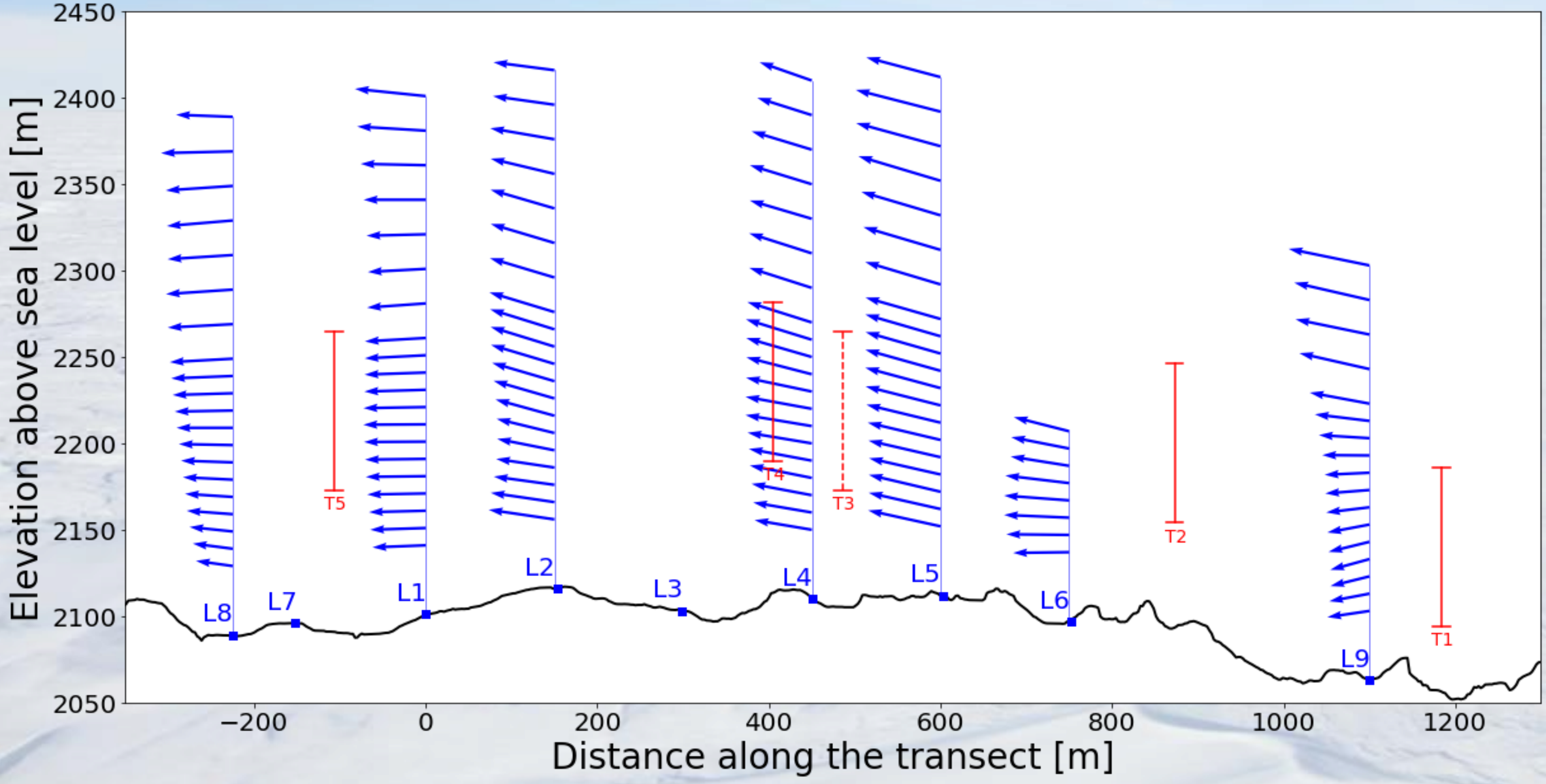
Let's go to the field: Windpower production at Gotthard



Wind-Doppler LiDARs are used to measure vertical profiles of wind speed (and direction)

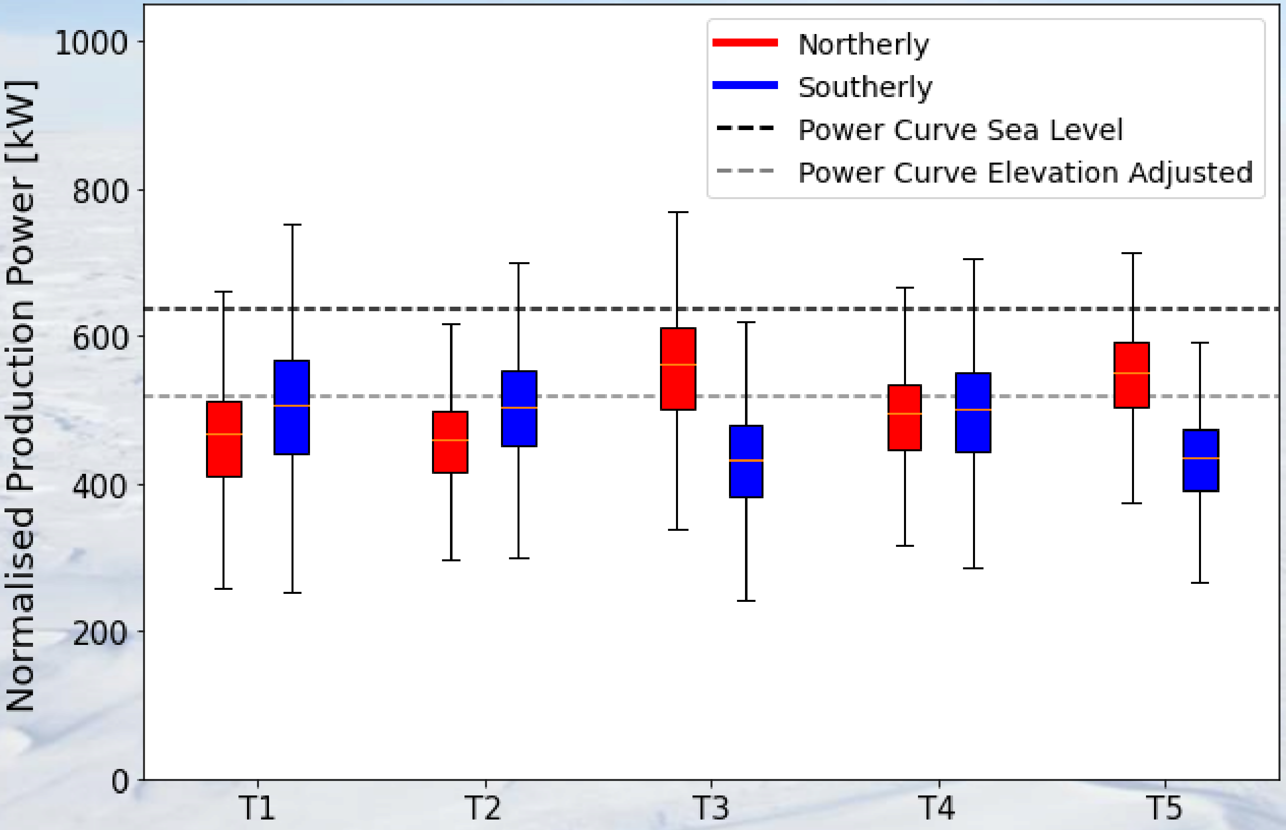
- Laser pulse
- Reflect on atmospheric particles
- Line-of-Sight Doppler shift

Let's go to the field: Lidar profile measurements along transect



The profile measurements for northerly wind show very complex spatial differences.

Turbine Performance at Gotthard



Some locations show “overperformance” others rather not. Adjustment is for density!

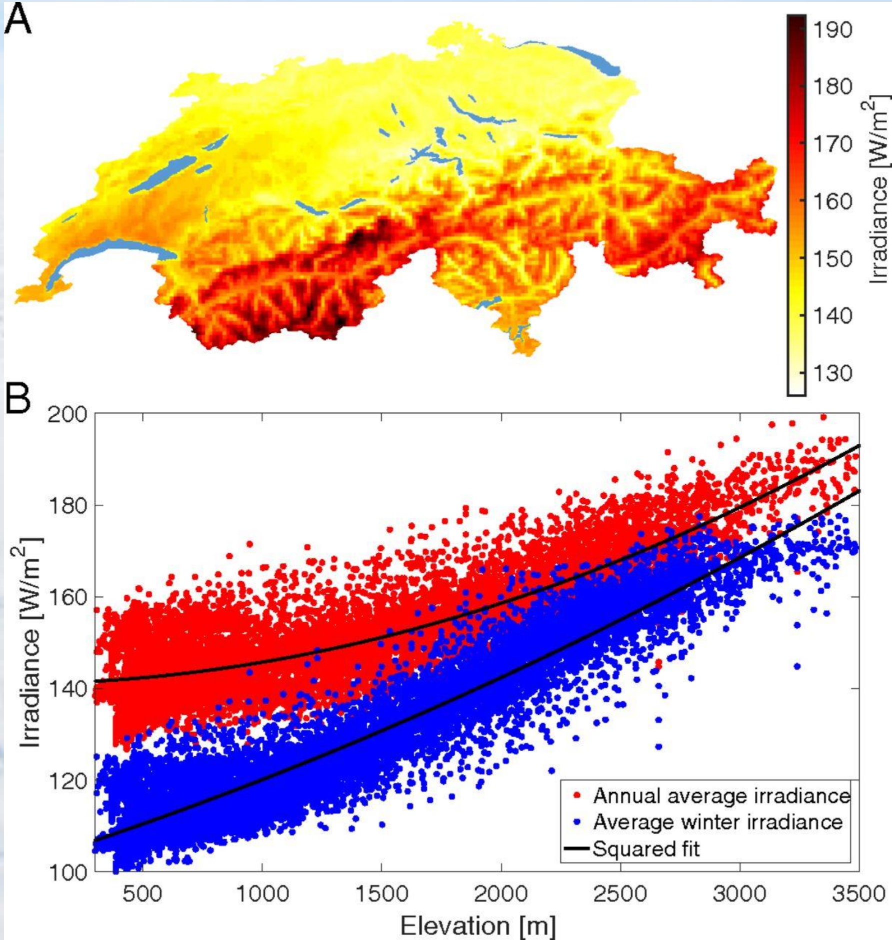
Second Summary

- Switzerland has untapped wind resources
- Mountain flows are complex, variable and need to be better understood
- Winds must be measured (e.g. with LiDARs) and modelled (Navier-Stokes or machine learning models)
- Wind provides important winter energy and is a steady source

Now going to solar PV, especially high-Alpine

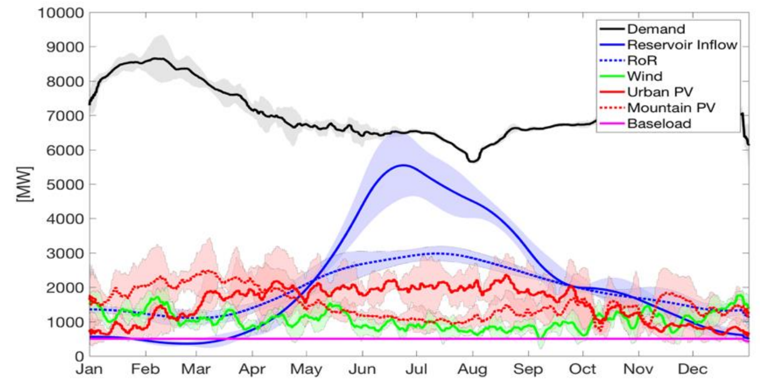
Distribution of incoming global irradiance (Heliomont product by MeteoSwiss) in Switzerland (2011 – 2016).

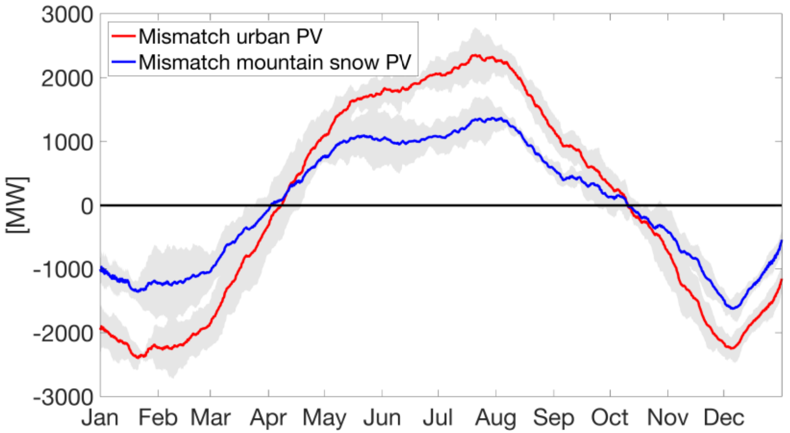
Winter shows an even stronger increase with elevation, which is due to clouds, fog, thinner atmosphere and



Annelen Kahl et al. PNAS 2019;116:4:1162-1167

Now going to solar PV, especially high-Alpine

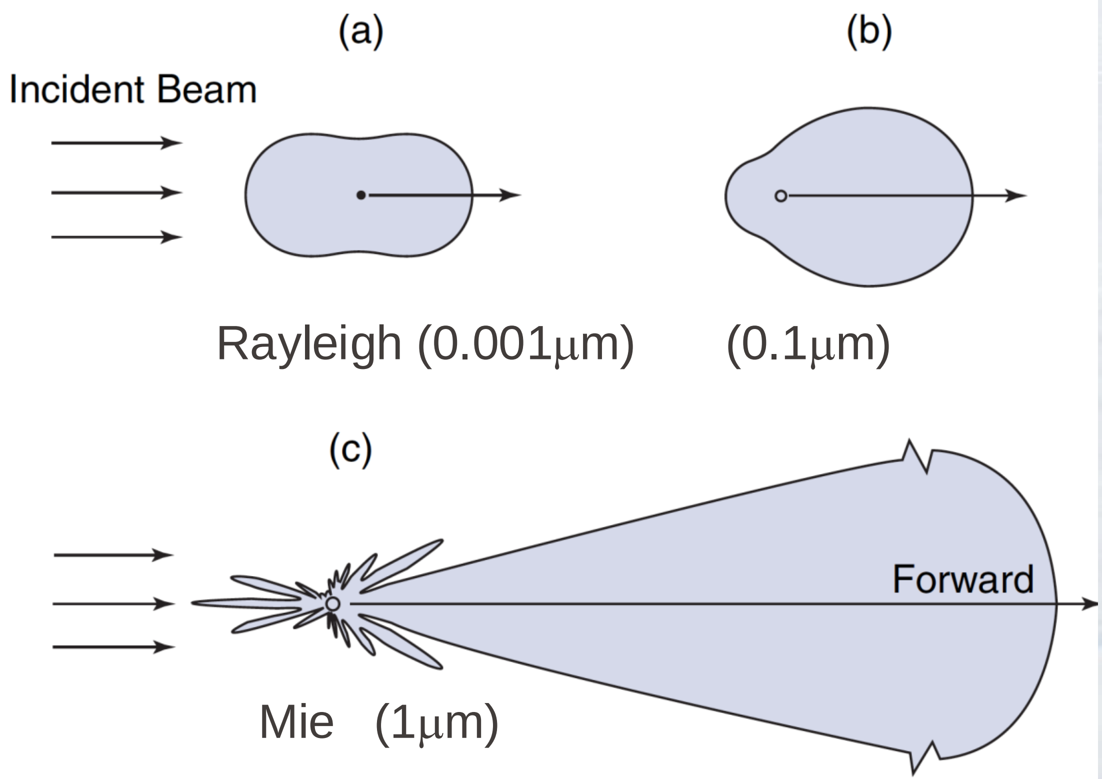




This mismatch reduction also reduces the required import of energy

	Panel tilt	PV area
urban	40°	53km^2
mountain	90°	42km^2

Forward scattering properties of snow plays a role for Alpine PV



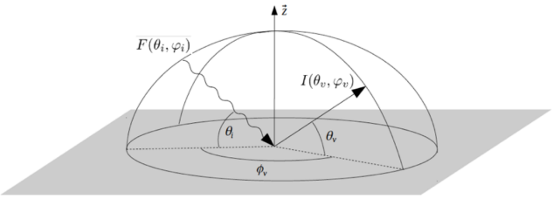
Snow is ”forward scattering”, multiple reflections from terrain and between clouds and snow-covered surface occur and increase local radiation fluxes.

Directional probability distribution for scattered radiation is shown on the left.

Forward scattering properties of snow plays a role for Alpine PV

- **Assumptions:**
- We know incoming shortwave radiation (direct and diffuse) at the surface
- Diffuse radiation from the sky is isotropic
- Broadband treatment is sufficient
- Geometric optics can be used

Anisotropy



F SW Flux density (W/m^2)

I Radiance (W/m^2/sr)

R Anisotropy Factor

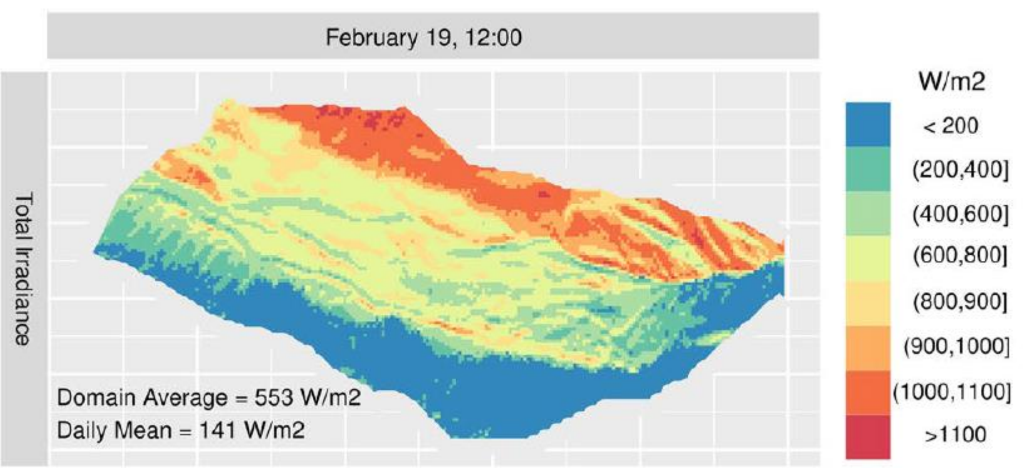
$$R(\theta_v, \varphi_v, \theta_i, \varphi_i) = \frac{\pi}{\alpha}\frac{I(\theta_v, \varphi_v)}{F(\theta_i, \varphi_i)}$$

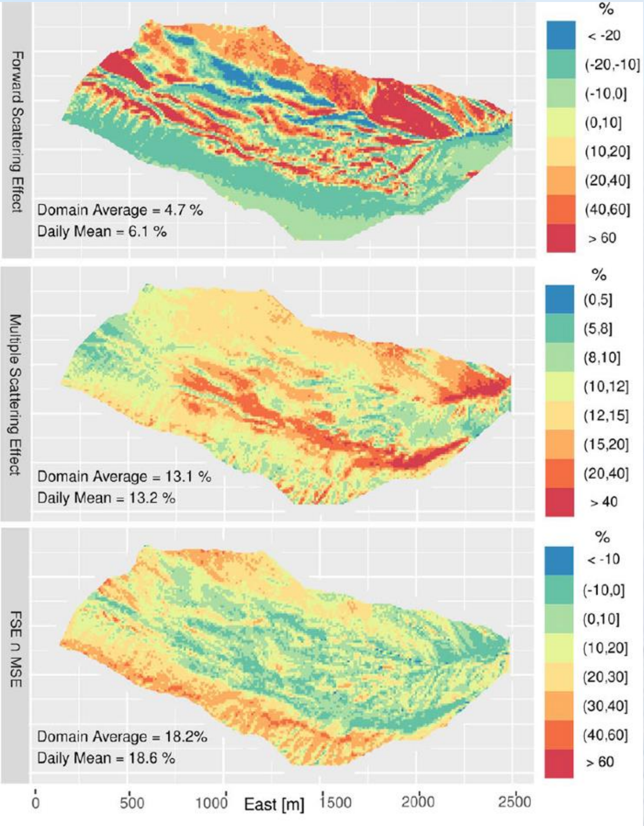
Broadband Bidirectional Reflectance Distribution Function (BRDF)

Albedo: $$\alpha(\theta_i,\phi_i) = \int_0^{2\pi}\int_0^{\frac{\pi}{2}} d\phi_v d\theta_v \rho(\theta_i,\phi_i,\theta_v,\phi_v) \sin\theta_v \cos\theta_v.$$

Von Rütte, Kahl and Lehning, JGR, 2021

Forward scattering properties of snow plays a role for Alpine PV

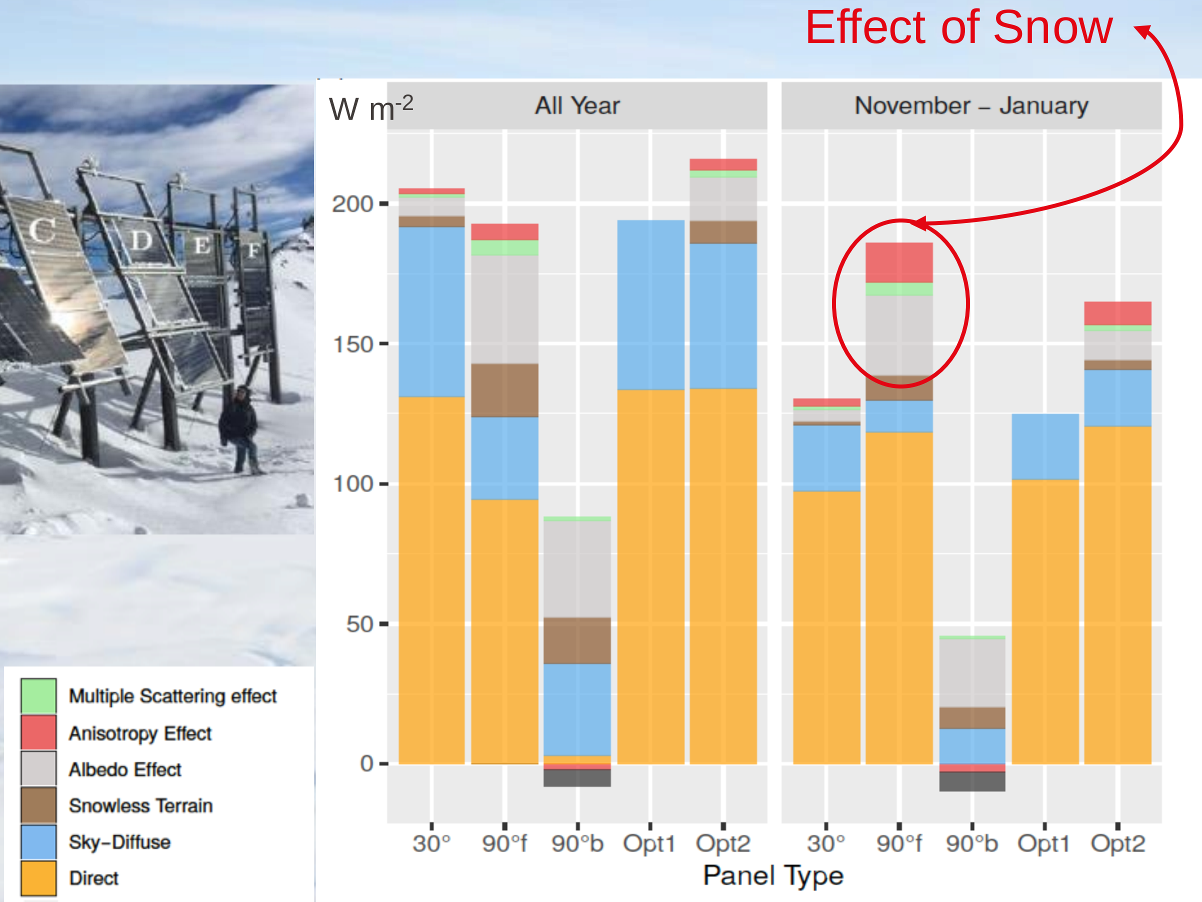




- **Main Points:**
- Sunny slopes profit from forward scattering
- Effect multiple scattering changes the mean
- Total effect on energy balance is limited (not shown)

Von Rütte, Kahl and Lehning, JGR, 2021

Forward scattering properties of snow plays a role for Alpine PV



Von Rütte, Kahl and Lehning, JGR, 2021

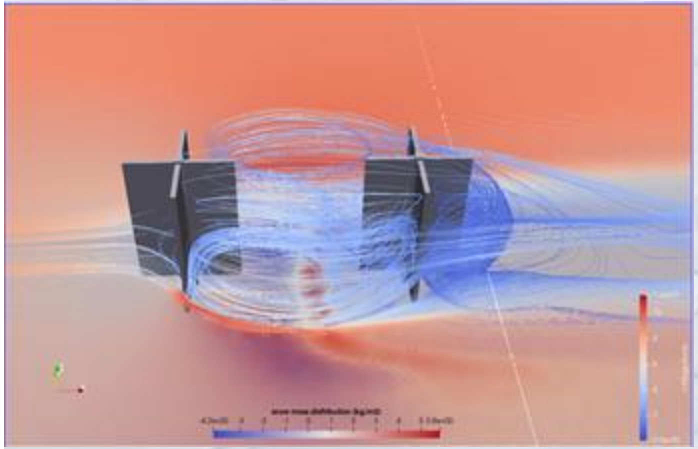
Third Summary

- Mountains have more radiation, especially in the winter
- This can be used for winter energy production with Alpine PV plants
- Snow (if present) locally increases the PV yield substantially
- Best places for PV installations can be predicted

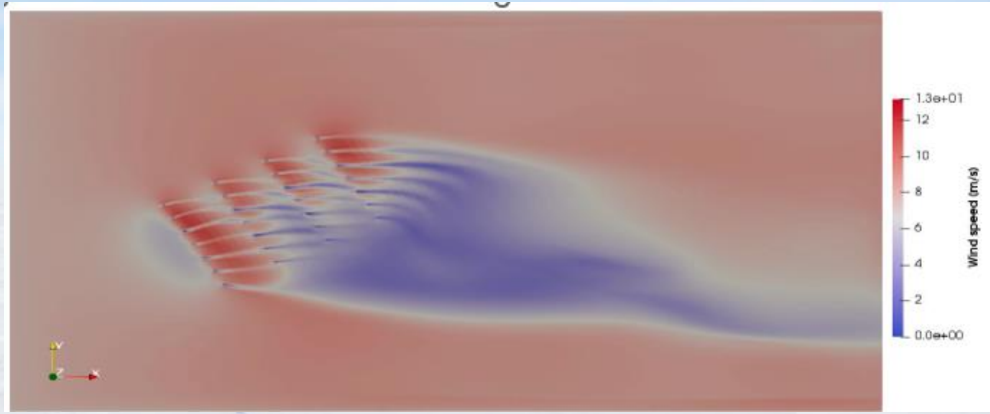
How do we keep the panels free of snow?

Snow is helping high production but also constitutes a potential hazard. Not only can it cover panels and prevent production, it can even damage the panels and carrying structures.

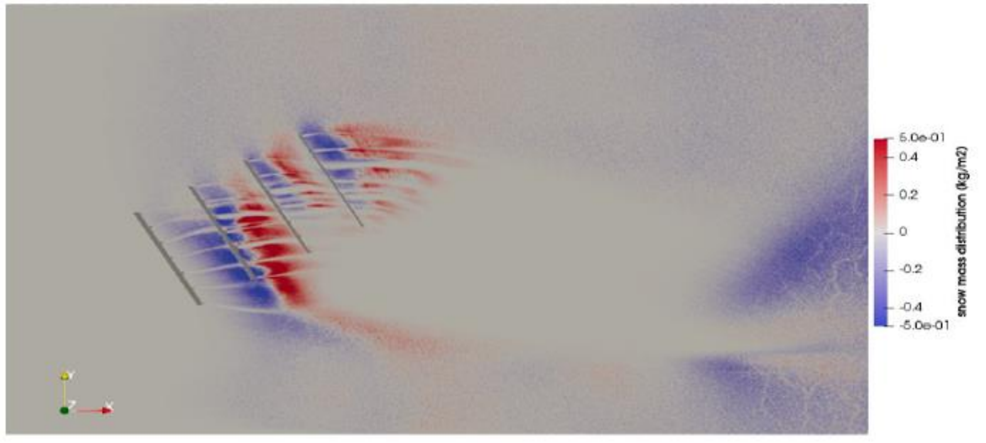
New Tools



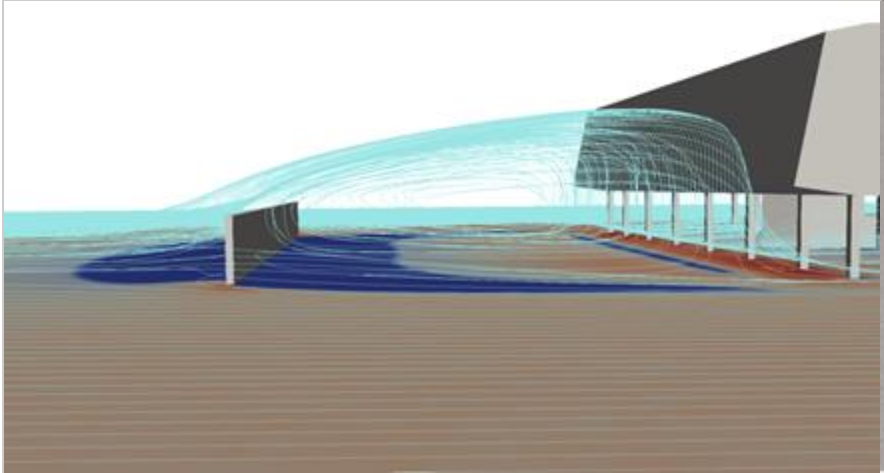
Windload on Alpine PV

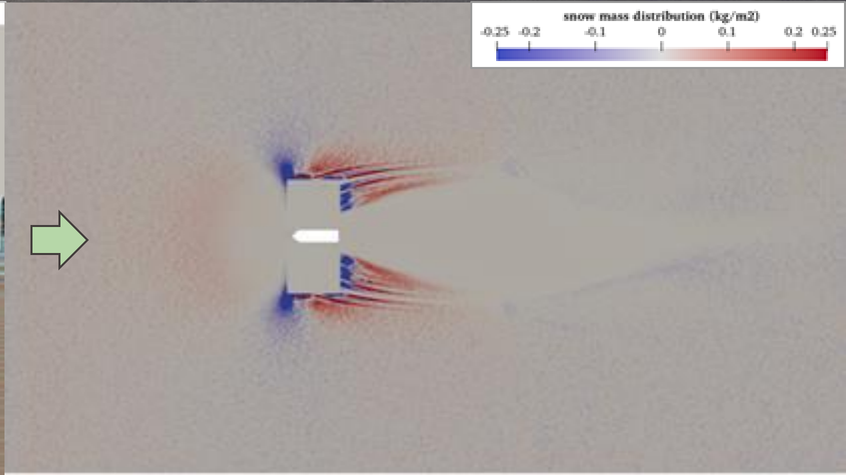


Snow Accumulation



Find design options for all types of man-made structures in snowy places





A personal environmental engineering solution

Fourth Summary

- Snow can be a problem for Alpine PV installations and other structures
- Using modern fluid dynamics and snow transport models, snow accumulations can be predicted and design options can be explored
- This is a rapidly evolving fields with potential for significant progress in a near future

Assessing the Urban (Energy) Environment (Present and Future)

Rapid Urbanization

↓

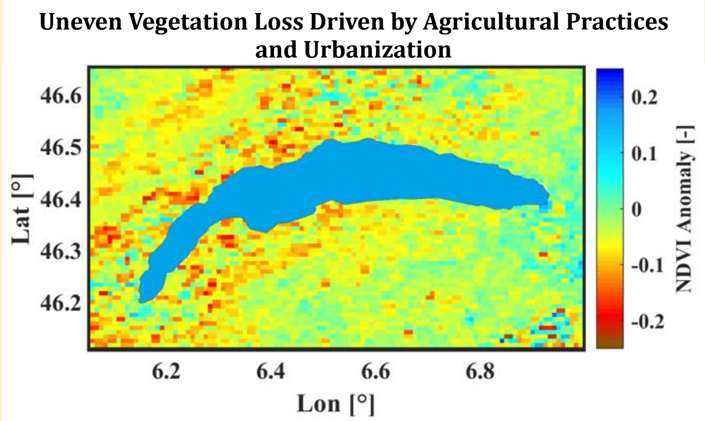
Land Use Change and Vegetation Loss

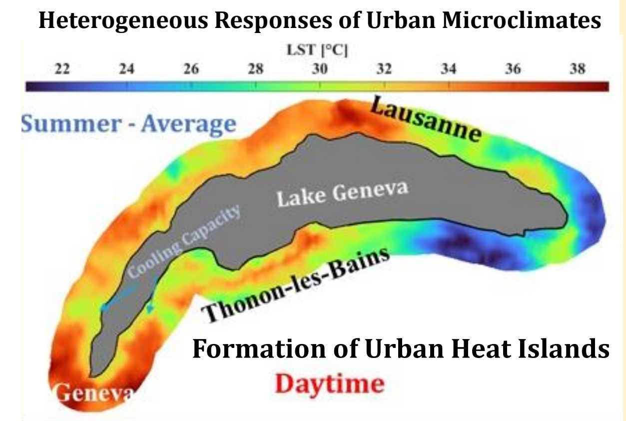
↓

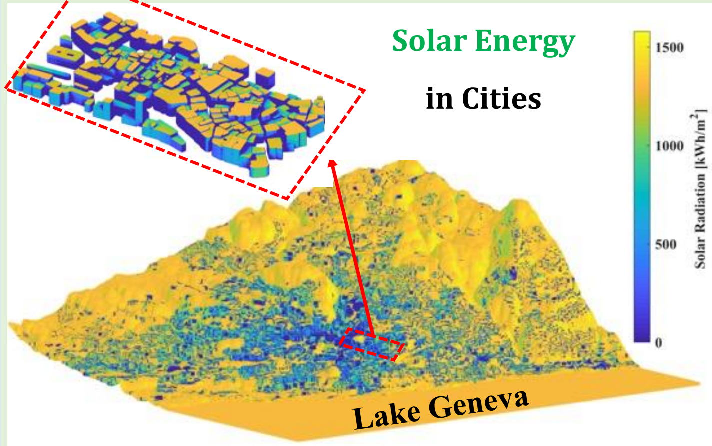
Climate Change

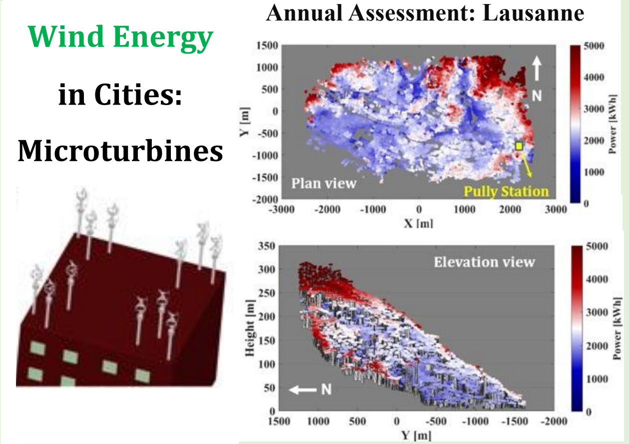
↓

Sustainable Solutions for Urban Energy









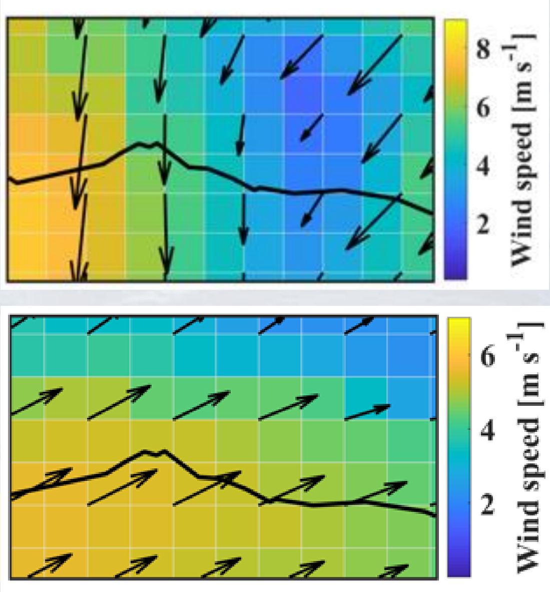
Assessing the Urban (Energy) Environment (Present and Future)

Development of a combined computational fluid dynamics (CFD) and machine learning (ML) approach to generate high resolution meteorological fields based on meteorological model forecasts.

CFD-MicroClimateModel

Machine Learning

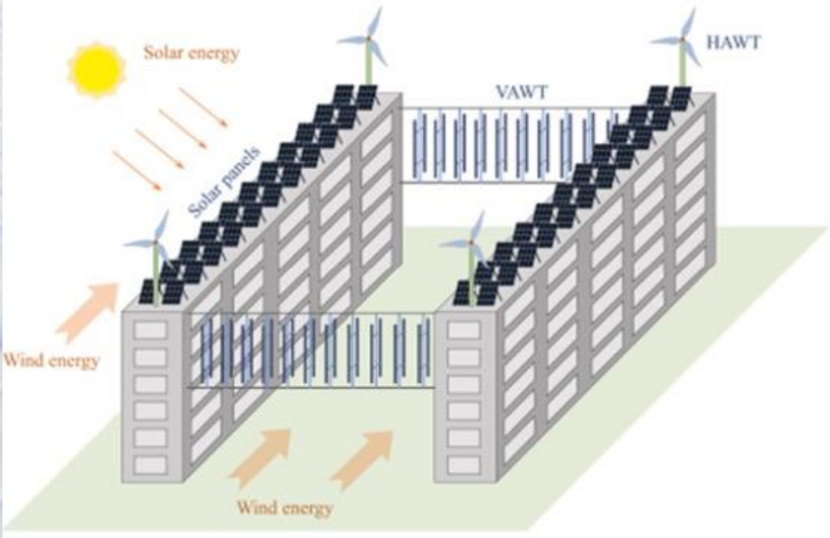
CFD-Mesoscale Model



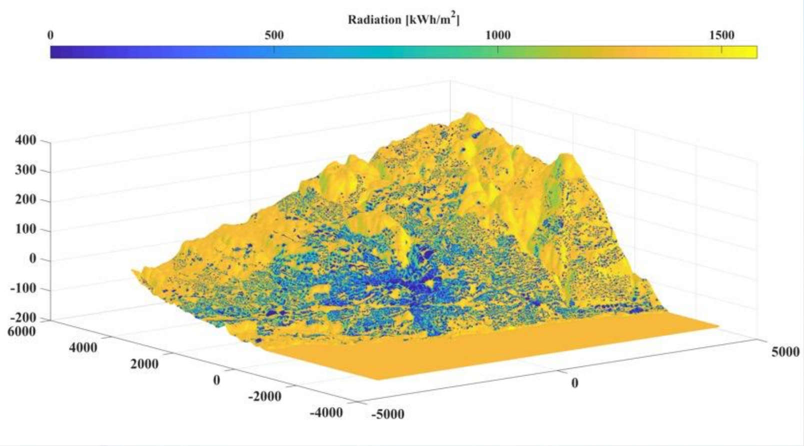
Wind Energy Assessment: Daily, Monthly, and Annual Analysis

Urban and Rural Energy Resources: A Comparative Analysis of Solar Radiation and Wind Energy Potential

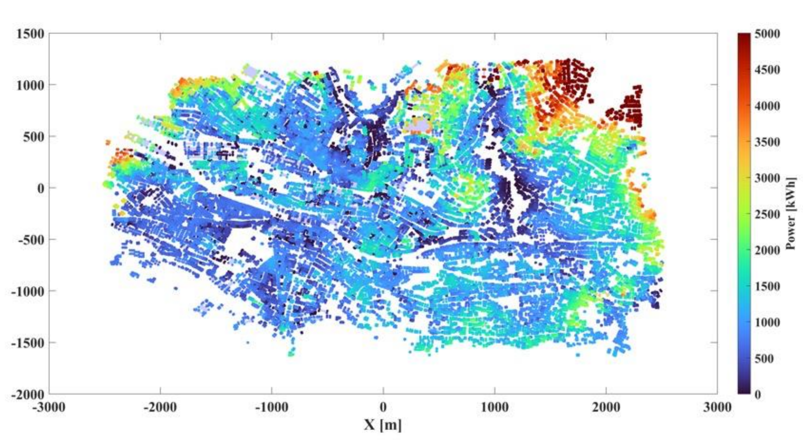
How can we determine the most effective spatial placement strategy for solar farms and wind turbines across diverse terrains and urban morphology to optimize energy yield and efficiency?



Annual Solar Energy Assessment: Lausanne



Annual Energy Output of the QR6 Turbine in Lausanne

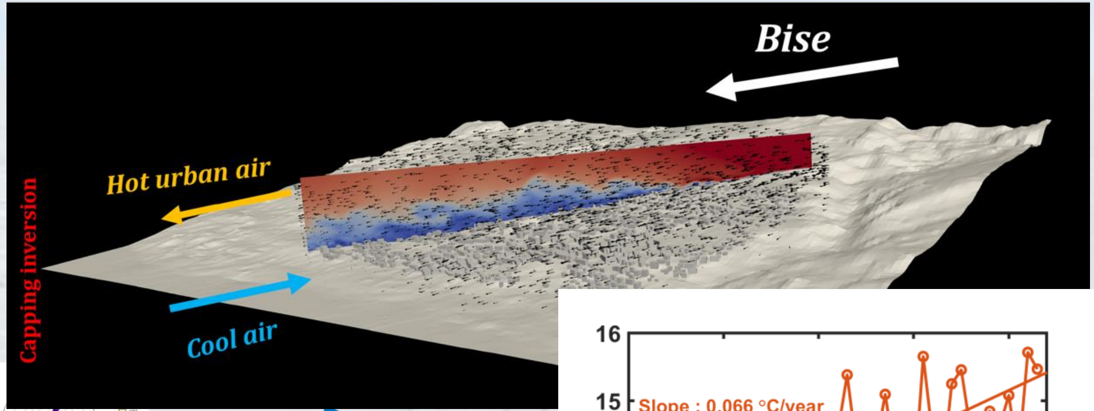


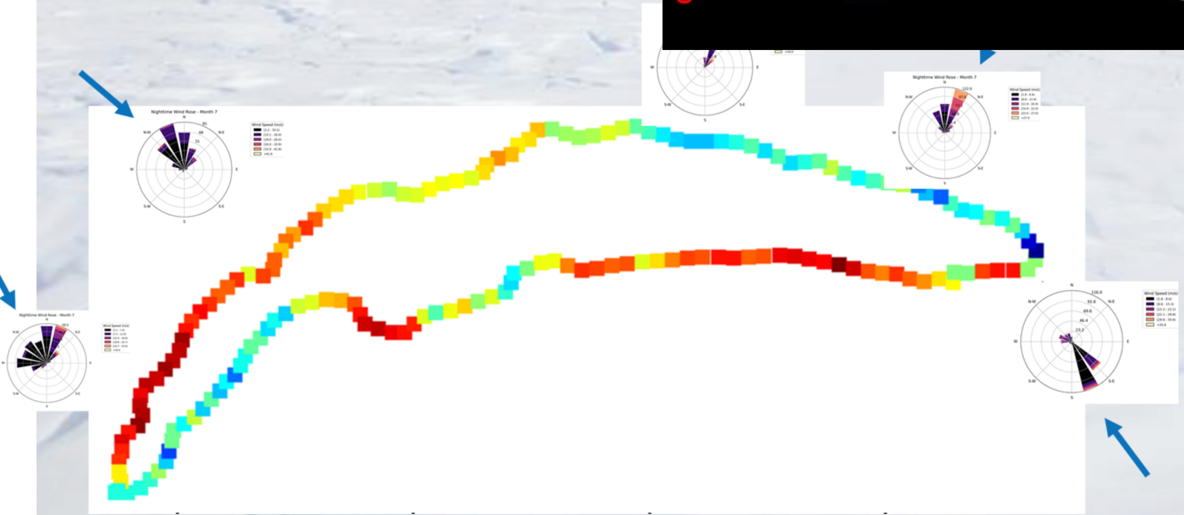
Assessing the Urban (Energy) Environment (Present and Future)

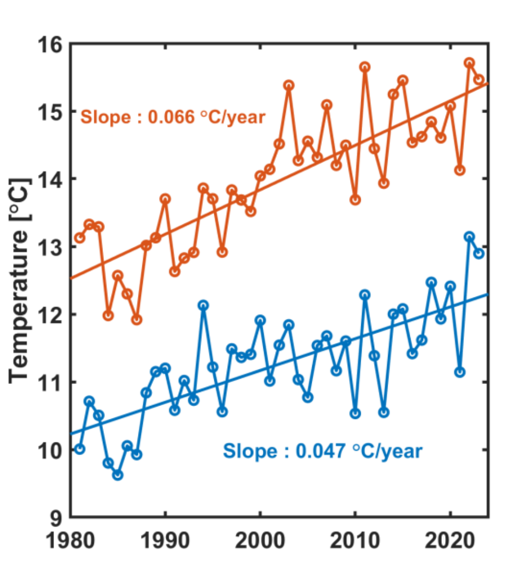
?

The intensity of lake and land breezes, driven by temperature gradients between the land and the lake, is evolving.

A reliable source of wind energy.



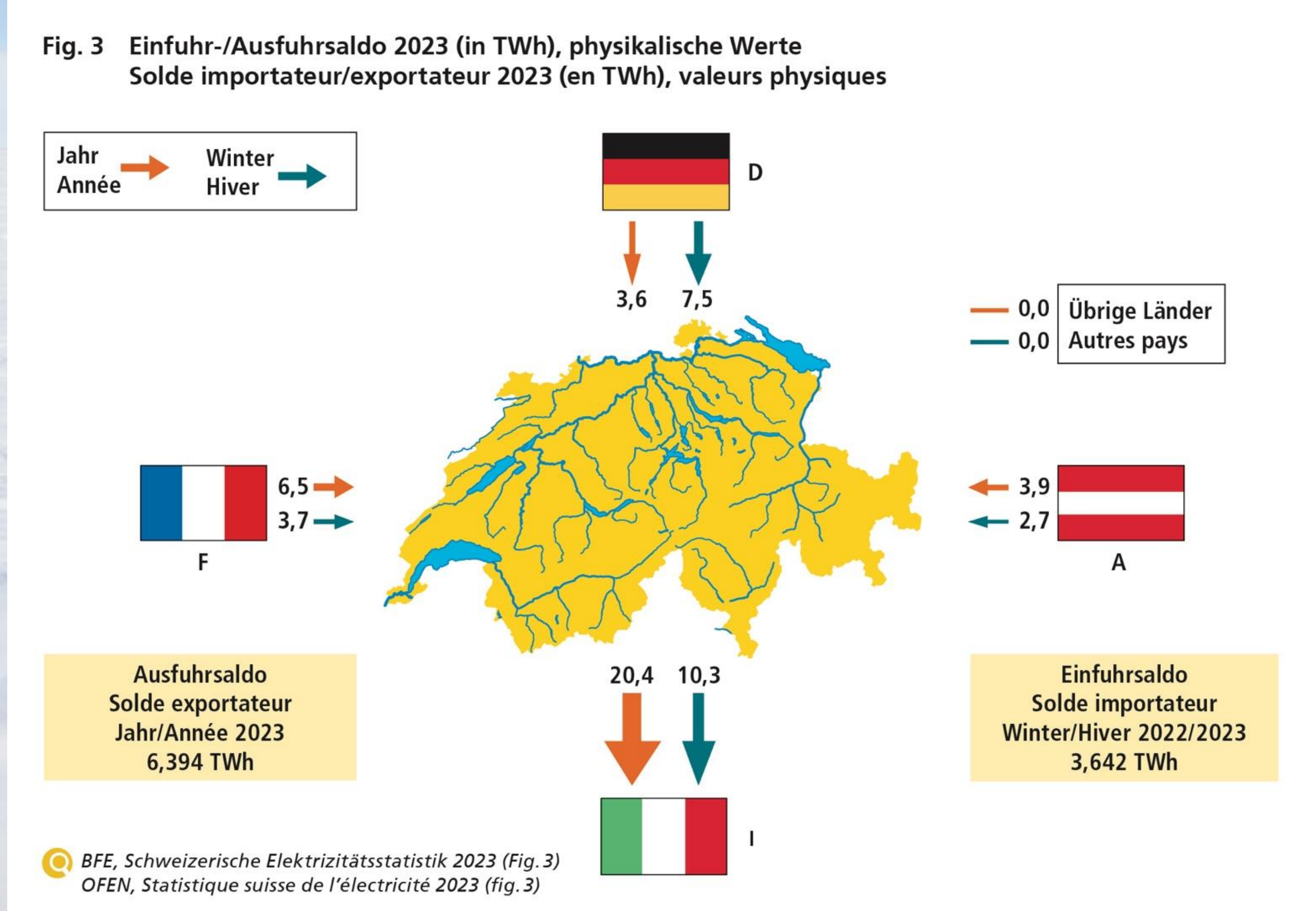




Fifth Summary

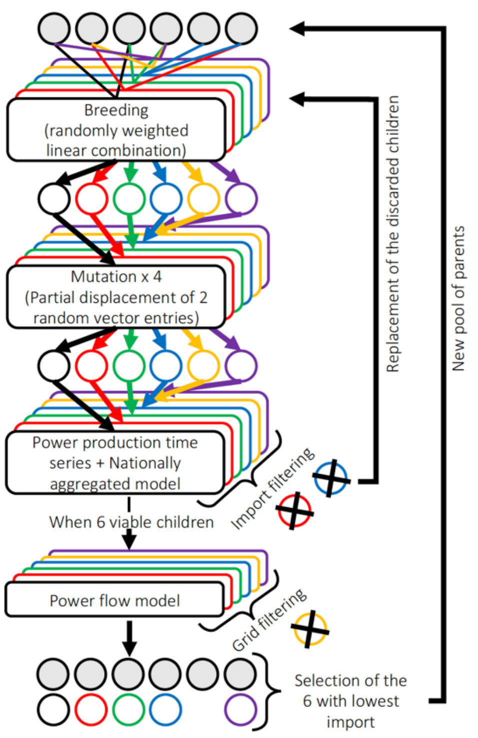
- Urban environments pose environmental problems and have a high energy demand
- Heat problems become more severe with climate change
- But there is a potential for renewable energy production “on urban sites”
- And the specific settings of urban centres need to be considered, for example lake breeze effects can be used for cooling and energy production

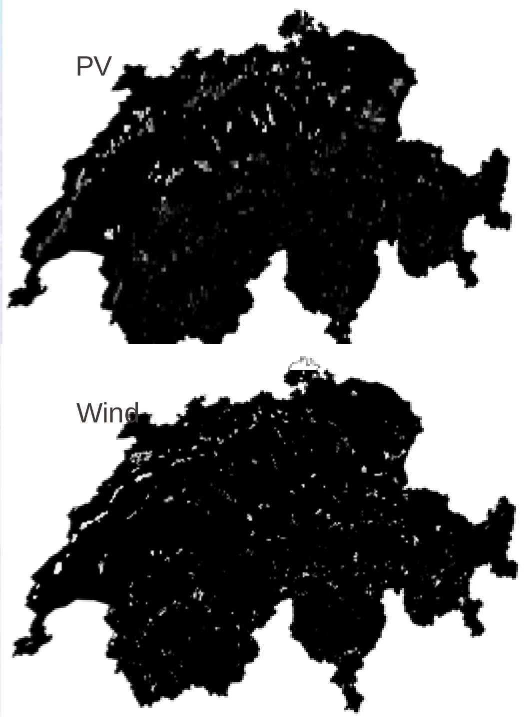
Optimized Installations and the Value of Weather Forecasts

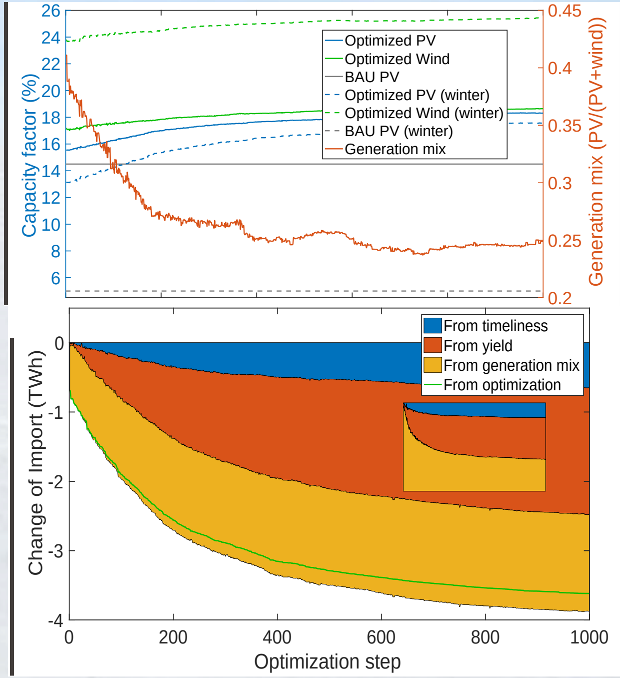


Optimized Installations and the Value of Weather Forecasts

Evolution strategy



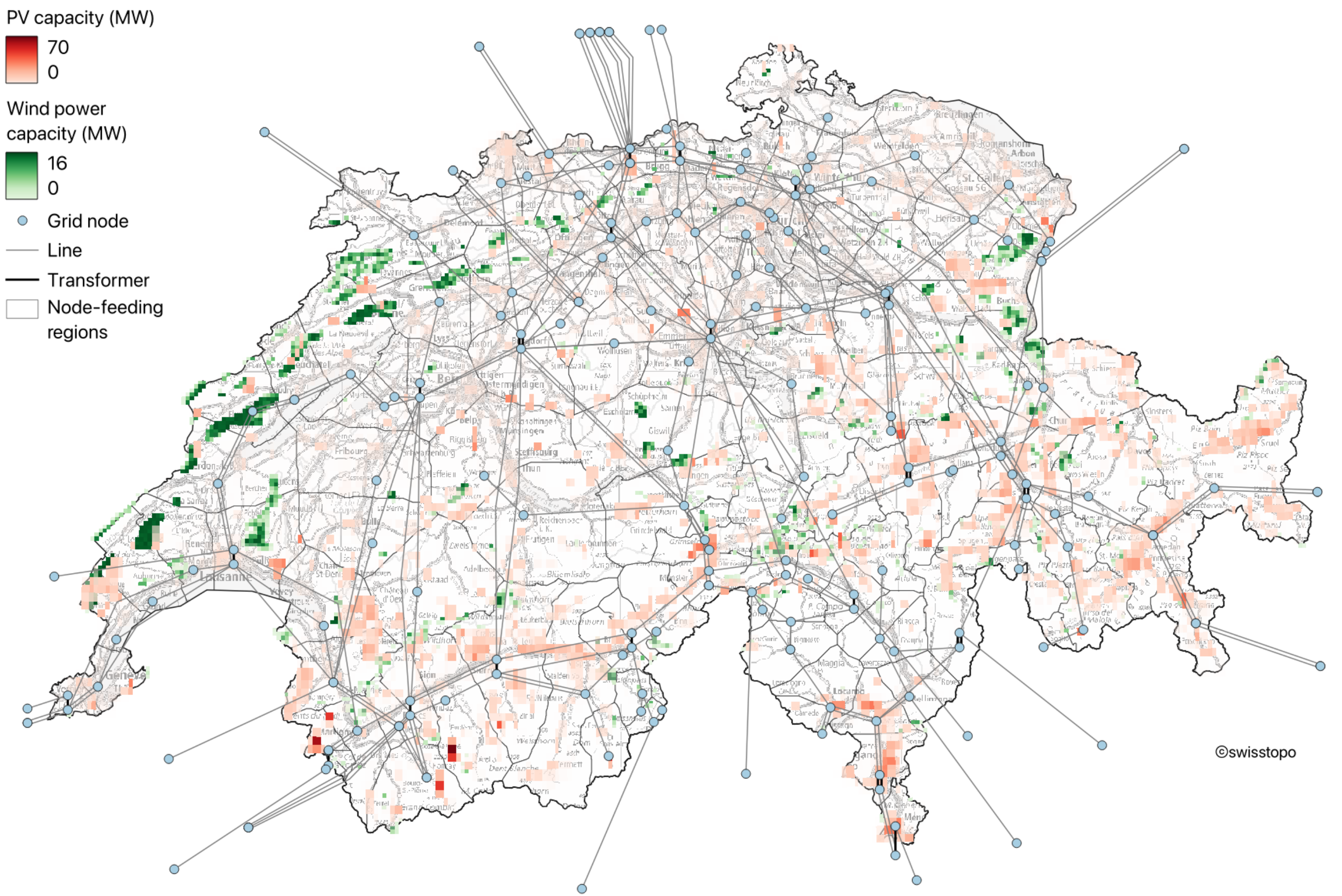




Dujardin et al., ERL, 2021

- Import reduced by 51% compared to initial solution
- 80% less import than a conventional urban PV scenario

Optimized Installations and the Value of Weather Forecasts

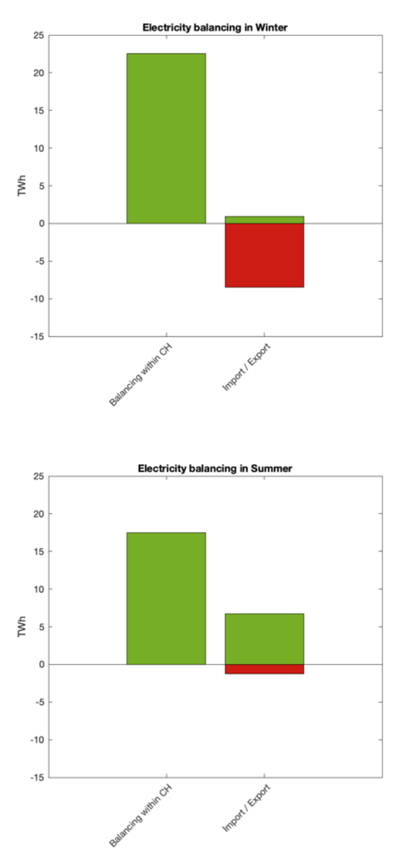


The distribution of solar and wind installations shown results in a stable supply given a forecasted demand in 2050 and assuming the weather year 2018. The system can be operated based on the current grid.

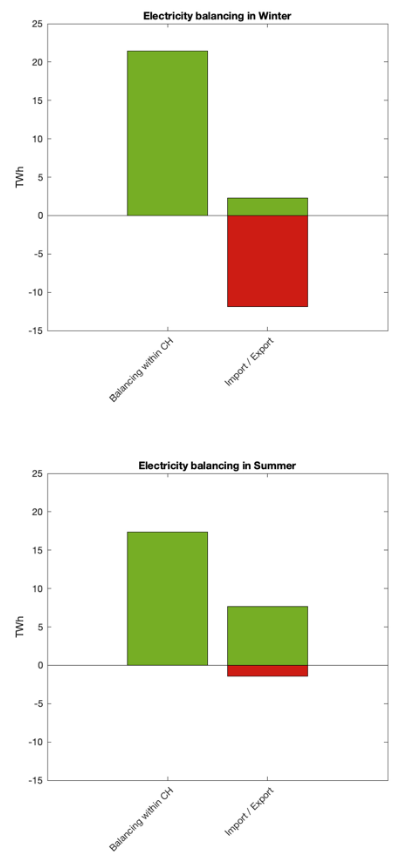
→ Try to explain the ”hotspots” of wind and solar installations!

Now artificially "forget" about the weather forecast

Weather is known



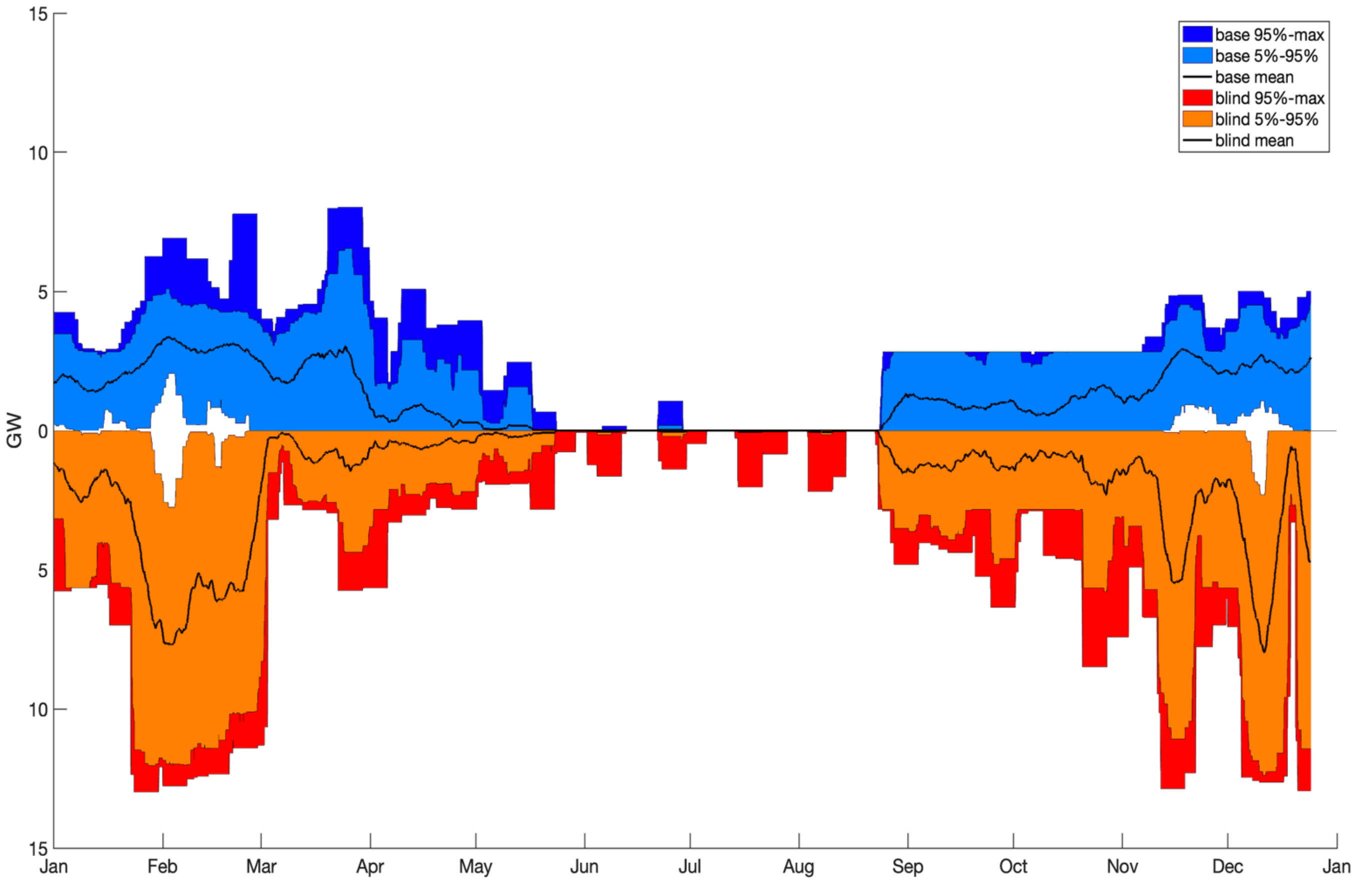
Weather is unknown



Required winter import increases by 36% if weather forecast is not considered in the operation of the hydro dams. Note that without other dispatchable generation sources such as gas turbines (or nuclear), hydropower is the only manageable source of energy considered. This is achieved with 16 GW solar and 12 GW wind installations.

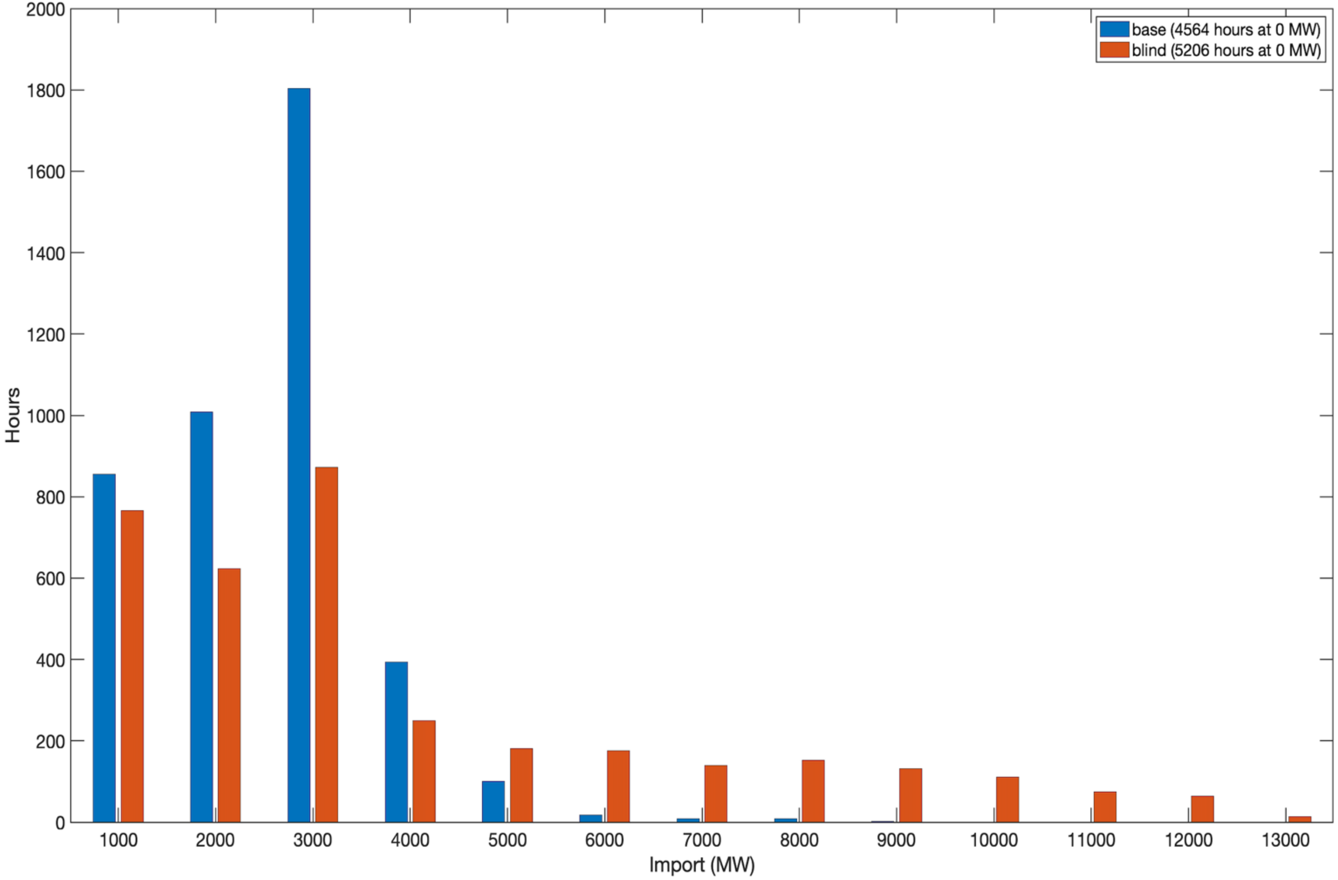
→ Try to calculate the value of weather through "saved import"!

Comparison of Import Dynamics w/o Weather Forecasts



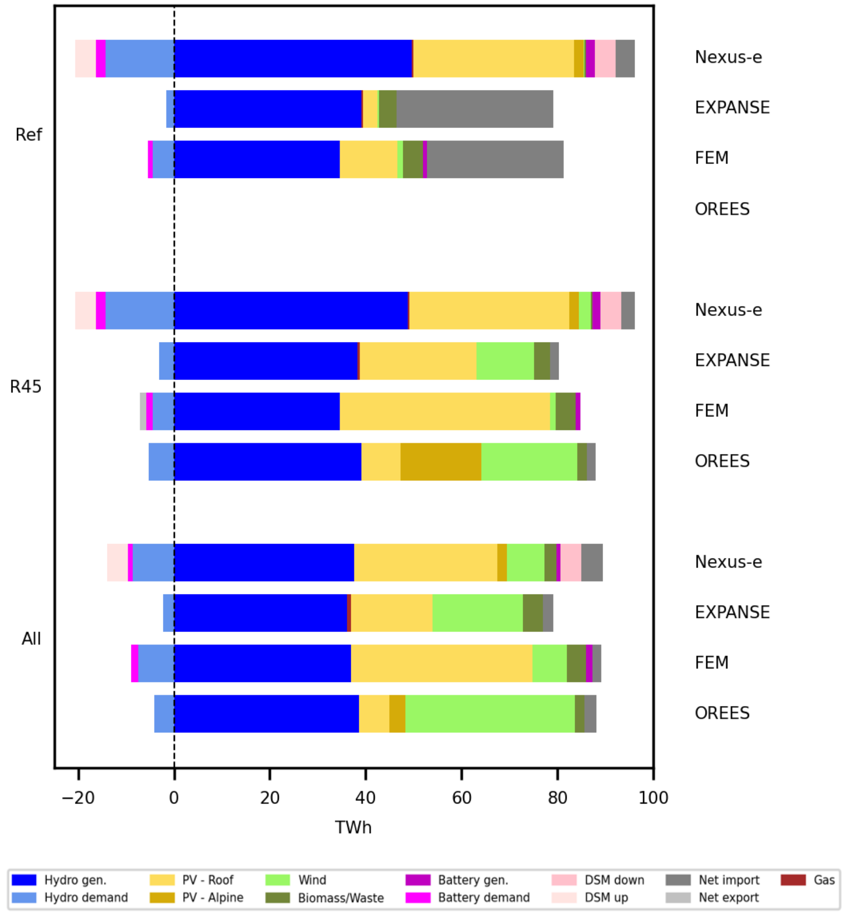
In the base scenario with weather forecast (blue) not only less import is required but import is much more stable in time. The case without weather forecast (red) causes more extreme import.

Comparison of Import Dynamics w/o Weather Forecasts



The more extreme import is also shown here by counting the hours for which a certain import value (x-axis) is required.

National Energy Scenarios for a Renewable Future



No target – TYNDP 2022 scenario

45 TWh target renewable generation

Add 5 TWh winter import and network capacity restriction

Policy Implications:

- Improve Solar- and Windexpress
- Generate positive reputation for de-centralized installation
- Support grass-root initiatives
- Stay "Alpine"

Final Summary

- Switzerland is a strong but dependent player in the European energy market
- With a mix of wind power and solar PV at optimal locations, winter import can be kept reasonable
- When considering the weather forecast, optimized operation of the hydropower generators yield a huge economic benefit
- Such optimized operations are beneficial for the grid and reduce peak import requirements
- Overall, a fully renewable electricity generation in Switzerland by 2050 is feasible but requires a massive effort